APPLICATION OF NANOFLUID LUBRICATION DURING MACHINING OF AEROENGINE GRADE STAINLESS STEEL

Thesis Submitted in Partial Fulfillment

of the Requirements for the Award of

Master of Technology

In

Production Engineering

By

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M.Tech Thesis

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CERTIFICATE

This is to certify that the thesis entitled, **"Application of nanofluid lubrication during machining of aeroengineering grade stainless steel"** submitted by **Mr. Shailesh kumar Dwivedi** in partial fulfillment of requirements for the award of Degree of Master of Technology in **Mechanical Engineering** with specialization in **"Production Engineering"** at National Institute of Technology, Rourkela is an authentic work carried out by him under my guidance and supervision. To the best of my knowledge the matter embodied in the thesis has not been submitted to any other University or Institute for the award of any Degree or Diploma.

Date: 30-05-2015

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ABSTRACT

The main problem associated with any metal cutting operation is introduction of undesirable elevated temperature at the cutting zone. Higher temperature at the tool-work interface becomes cause for failure of cutting tools and formation of micro cracks. The reason behind high temperature formation is high rate of friction between tool-work and tool-chip interface caused by continuous rubbing action of forming chip with tool face and the shearing failure of chip. To overcome this problem the solution which is most widely used comes into picture, is implementation of cutting fluid. The purpose of cutting fluids is to provide cooling and to reduce the friction between tool and work piece at the shear zone. It is well known that application of minimum quantity lubrication (MQL) as a cutting fluid is more preferable than normal flood cooling technique because of many advantages over normal flood cooling. To increase the effectiveness of MQL addition of nanoparticles is done. In the present work a water-soluble-oil-based MQL technique with different volume fraction of aluminium oxide (Al_2O_3) nanoparticles is used as the cutting fluid for turning of 17-4 PH grade stainless steel. Experiment is carried out using 4 different volume concentrations inclusion of Al_2O_3 nanoparticles in the base fluid with MQL lubrication technique and the experimental results are plotted on the basis of that. The results clearly indicated the beneficial aspects of Al_2O_3 in reducing the cutting temperature by virtue of enhanced heat transfer characteristics of nanoparticles of Al_2O_3. It is observed that the rate of temperature dissipation from tool and work piece increases on increasing the volume fraction of Al_2O_3 nanoparticles and dynamic fluctuation of cutting forces also reduces during introduction of nanoparticles. On the other hand major decrement on the cutting force, tool wear rate and chip thickness along with improved surface quality has also seen, on percentage increment in concentration of Al_2O_3 nanoparticles.

Keywords*: MQL, aluminium oxide, conventional water-soluble-oil, machining, 17-4 PH ss.*

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NOMENCLATURE

MQL – Minimum quantity lubrication

CNT – Carbon nanotube

MWCNT – Multiwall carbon nanotube

ND – Nano diamond

CA – Compressed air

cBN – Cubic boron nitride

PH – Precipitation hardened

DAQ - Data acquisition system

EDS – Energy dispersion spectrum

FESEM - Field emission scanning electron microscopy

V_c – Cutting speed (m/min)

f- feed (mm/rev)

a_p – Depth of cut (mm)

T – Machining time (s)

F_z – Tangential cutting force (N)

F_y – Radial force (N)

F_x – Feed force

μ - Coefficient of friction

α – Orthogonal rake angle

ζ – Chip reduction coefficient

R_a – Average surface roughness (μm)

θ – Nozzle angle

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CHAPTER 1

INTRODUCTION

1. MACHINING

Machining is one of the essential and challenging tasks in the manufacturing industries which involve a controlled removal of material from the substrate by using a cutting tool. As machining involve plastic deformation of workpiece material and also friction between tool-chip and tool-woekpiece interface these both phenomenon needed high amount of energy which further converted into heat. While machining low strength alloys there is less amount of heat generation take place but machining of ferrous and other high strength alloys are associated with larger amount of heat generation. The distribution of heat generated is shown in Fig. 1.1. The dissipation of this generated heat is one of the important factors as per good machining requirements. If the generated heat is not dissipated effectively, may cause for reduced tool life, poor surface finish of machined face and thereby reduction in overall performance of the machining process obtained as a result. Although high speed machining is desirable condition in most of the cases, the penalty of higher heat generation needs to be minimized.

Therefore, there is a need to control friction between the tool-chip and tool-work, and reduce the heat generated. For this purpose a bulk amount of cutting fluid is forced to spray on-to the cutting zone. The cutting fluid cools the cutting zone and provides lubrication for tool–chip and tool-work contact, thereby reducing the friction and also the temperature generated. This provides less tool wear, a good surface, and less cutting forces during machining. Even with all of these benefits, there are also negative impacts of cutting fluids such as carrying problems, disposal problems, the toxic nature of fluid, and also the environmental pollution such as water pollution, soil pollution, and air pollution [2, 3]

This need gave birth to many alternative techniques to minimize the quantity of cutting fluid used [4]. Some such techniques which came forward were:

- Dry machining
- Use of coated tool
- Wet machining

1.1 Dry machining

This is an environmental concern call for the elimination of the cutting fluid in metal cutting operation. In the recent past, a lot of interest is being taken in the machining without using cutting fluid. When no cutting fluid is used during machining, it is called dry machining. Dry machining associated with low cutting speeds and easily machinable materials. Usually, dry machining is not appropriate in cases where great surface finish and high precision in dimensional stability are required. This is so because dry machining involves high temperature generation which enhances the chances of formation of built up layer. This built up layer due to its unsteady nature breaks and takes away a portion of tool material due to its high adhesive nature causing tool wear. The broken segments when stick to the machined surface deteriorates the surface finish. Thus, dry machining without any lubricating and cooling enhancement is not preferred in general cases of machining.

1.2 Use of coated tool

It has been well established that advanced surface coatings on cutting tools improve wear resistance by modifying the contact conditions between the chip and tool interface. As a result of the recent developments in cutting tool industry, coated tools have made a major contribution to the metal cutting operations in terms of machining quality, tool life and cutting time. The confront of modern machining industries is aimed mainly on the getting of high quality, surface finish, in terms of work piece dimensional accuracy, high production rate and less wear on the cutting tools. So as to avoid the usage of cutting fluids during machining processes, nowadays coated tools are gaining fame. In this method the tool inserts are provided with a coating which can serve the following purposes.

1. It should have low thermal conductivity so that it does not allow any heat to enter into the bulk material of the tool.

2. It should have good resistance to abrasion wear and must possess high thermal and chemical stability.

3. It must possess low friction coefficient and must be securely bonded to the tool substrate material.

Most regularly used coating materials are titanium based coating such as TiAlN, TiN, TiAlCrN etc.

1.3 Wet machining

1.3.1 Properties of cutting fluid

Cutting fluid also known as lubricants and coolants as it fulfills both the desired purpose. It serves the cooling effect to minimize the negative thermal affects and lubricating effect to provide better surface finish. Cutting fluids are used extensively in machining operation to:

- Cool the cutting zone, thus reducing workpiece temperature and distortion, and improving tool life.
- Reduce friction and wear, hence improving tool life and surface finish.
- Reduce forces and energy consumptions.
- Wash away chips.
- Protect the newly machined surfaces from environmental attack.

The following are the essential properties, which cutting fluids must possess in order to fulfill their desired function:

- A good cutting fluid is defined with its large specific heat capacity and high thermal conductivity.
- It should have low viscosity in order to easily enter through small gaps.
- It should be non corrosive, non toxic and should not react with workpiece and tool material.
- It should be ease as per availability and should not be much expensive.
- It should have high flash point to maintain its properties.

It should be chemically and physically stable.

1.3.2 Types of cutting fluid

Cutting fluids can be classified in to two following broad category:

- Water miscible cutting fluids
- Mineral oil base cutting fluids
- Cryogenic cutting fluid

1.3.2.1 Water miscible cutting fluids

In water miscible cutting fluids, water stands as a main base fluid. Water is well known for its excellent cooling property. Thus water miscible cutting fluids have good heat absorbing capacity. Water miscible cutting fluids are a mixture of water soluble oil and water. Generally emulsifiers (soap like substance) used as a water soluble oil, when it get mixed with water in a small quantity a milky kind of fluid produces, which used to supply in cutting zone area.

1.3.2.2 Mineral oil based cutting fluids

These oils are mixture of several mineral oils or vegetable oils with no concentration of water. Some additives compounds such as phosphorous, sulphur, chlorine based can be added to base fluid in order to enhance their cooling and lubricating properties.

1.3.2.4 Cryogenic cutting fluid

Cryogenics is defined as the study of the production and behavior of materials at very low temperatures (below −150 °C, or 123 K). Mostly liquid nitrogen is used as the cryogen material. The use of liquid nitrogen as a cryogenic coolant in metal cutting has received renewed recent attention because liquid nitrogen is a safe, clean, colorless and non-toxic coolant that requires no expensive disposal and can significantly improve tool life [5]. It constitutes about four-fifth of the atmospheric gases. Its boiling point is -198.79ºC and melting point is -210.01ºC. During machining, the cryogenic coolant is supplied to the machining area (maximum heat zone area). The coolant takes heat by convection and drops down the maximum temperature reached thus contributing in tool life enhancement.

1.3.3 Conventional flood cooling

Conventional flood cooling is a traditional technique of cooling and lubrication of cutting zone. Under normal flood cooling flow rate typically ranges from 10 l/min (0.01 m^3/min) for single-point cutting tools to 225 l/min (0.225 m^3/min) per cutter for multiple-tooth cutters, such as in milling. In operations such as drilling and end milling, fluid pressures in the range of 700-14000 kPa are used to wash away the chips. Despite all of these benefits, there are also negative impacts of cutting fluids such as:

- Disposal of cutting fluid
- Cost of cutting fluid
- Spreading of cutting fluid around the machine

- Harmful residuals
- Disposal of wet chips
- Less visibility

1.3.4 Minimum quantity lubrication (MQL)

Minimum quantity lubrication is one of the most preferable techniques now a day as a cutting fluid purpose due to its capability of giving the good results with only small consumption of resources(power, cutting fluid). In this technique of cooling and lubrication a typical flow rate of cutting fluid in the range of 50-500 ml/h is directly applied to the cutting zone. Unlike normal flood cooling this technique is free from fluid disposal problem as it takes very small quantity for machining. Since this technique involves significantly lesser amount of cutting fluid, this technique is also termed as 'near dry machining' or 'micro lubrication' or 'spatter lubrication'.

Methodology

This technique concerns with the application of aerosol (mixture of highly compressed air with the typical pressure of 4-6 bar and cutting fluid) supplies through a specially designed nozzle with the hole diameter in the range of 1-2 mm. As in this method small droplets of aerosol directly comes in contact with the cutting zone, within fraction of time it gets evaporated due to very high temperature of cutting zone. Evaporation involves the extracting of latent heat from the machining area. Thus, this method concern with evaporative heat transfers rather than convective heat transfer. Since evaporative heat transfer is more efficient over convective heat transfer in terms of extracting heat, MQL for sure has extra benefits over normal flood cooling technique.

Advantages of minimum quantity lubrication

Minimum quantity lubrication technique has several advantages over conventional flood cooling, which can be summarized as below:

- It consumes relatively very less amount of cutting fluid thereby making the process almost clean and dry.
- As per small amount of cutting fluid less vaporization takes place, which is more environmentally friendly and less harmful for the operating worker as per health concern.
- As the process involves high pressure of air, it helps small droplets of aerosol to reach directly over to cutting zone easily.
- The mixture of highly pressurized air and cutting fluid easily flushes the forming chip effectively thereby making the chip handling task much easier.
- The machining processes which concerns with MQL is more productive with increased tool life and better surface finish of workpiece.

Application of minimum quantity lubrication

Minimum quantity lubrication fulfills the desire of almost all the machining process where the cooling and lubrication is must. The machining processes in which MQL has wide application are turning, grinding, drilling and milling.

1.3.5 Nanolubrication

On account of emerging ‘nanotechnology’ the concept of nanofluid lubrication has been developed. Nano lubrication is a process of effective cooling and lubrication of cutting zone during any machining process by involving nanofluid instated of normally used cutting fluids.

Nanofluids

In order to enhance the effectiveness of MQL and flood cooling, nanofluids have been developed. Nanofluids are engineered colloidal suspensions of nanoparticles (size of 10-100nm) in the base fluids. As MQL is already known for its better performance over conventional flood cooling, MQL is the best option as a base fluid for nanoparticles. Saidur et al. has shown a comprehensive review on applications and challenges of nanofluids. It has been found that even at very low particle concentration, nanofluids have a much higher and strongly temperature-dependent thermal conductivity, which is considered to be a key parameter for enhanced performance for most of the machining applications. When nanoparticles supplies along with base fluid it comes with ball bearing effect because of its nano range of size and due to its high thermal conducting nature extraction of heat becomes easier. Due to high heat dissipation rate, less tool wear results and due to cushion effect (ball bearing effect) of nanoparticles better surface finish obtain. Nanofluids proved itself best as an option for any machining process. As it is difficult to obtain standard similar size of particles when it comes in the range of nanometre, thereby specific density may differ from each other. In this way nanoparticles may have tendency to get settle down or float depending upon the cutting fluid used. To overcome this problem ultrasonic vibrator used to mix nanoparticles in the cutting fluid thoroughly. As per availability different types of nanoparticles can be used in order to achieve best cooling and lubricating property. Some of the nanoparticles which has wide applications now a days are:

- Molybdenum disulfide nanoparticles
- Aluminium oxide nanoparticles
- Silver nanoparticles
- Graphite nanoparticles
- Carbon nanotubes etc.

CHAPTER 2

LITERATURE REVIEW

2.1 Effect of nanofluid lubrication on different machinability characteristics

It has been observed that under MQL turning and high-speed milling of steel alloys conventional cutting fluid application technique fails to penetrate the chip–tool interface and thereby not able to cool the heat affected cutting zone effectively [3,7-8]. Kamata et al. investigated dry MQL machining of super alloys, which are widely used in modern industry due to their superior mechanical properties such as corrosion and heat resistance, and found the MQL technique effective in terms of giving performance. The researchers claimed that there is rapid growth in tool wear in case of machining of super alloys because of a elevated cutting temperature and powerful adhesion between the tool and work material appearing due to their low thermal conductivity and high reactivity. Hence, generally in this type of situations, the MQL technique with high thermal conductivity of coolant is favored. On account of emerging nanotechnology, high thermal conductivity fluids called 'nanofluids' have been developed. Nanofluids are engineered colloidal suspensions of nanoparticles (10–100 nm) in base fluids. When the things comes to undesirable high elevated temperature it has been found that nanofluids have a much higher and strong temperature-dependent thermal conductivity property even at very low particle concentration, which can be considered as a key factor for improved performance for many of the machining applications [6] .

2.1.1 Effect on cutting forces

Sarhan et al. worked with the mixture of SiO_2 nanoparticles and ordinary mineral oil as a lubricant. Machining progressed on vertical milling machine. They were used two types of lubrication—first, the ordinary mineral oil itself and, second, the SiO2 nanoparticles (0.2

wt%) inclusion with the same mineral oil. Mark able decrement in the power, cutting force, and specific energy requirements can be clearly seen on inclusion of nanoparticles lubrication in comparison with ordinary mineral oil.

Setti et al. has observed the effect of Al_2O_3 nanofluid with MQL in grinding operation which was performed on a surface grinder with SiC grinding wheel. The researchers followed the Taguchi experimental design technique and made a model for prediction of surface finish quality and participating grinding forces. In this study, results found with nanofluid were compared with the results found with pure water and conventional coolant. They were observed that nano Al_2O_3 particles bring down the grinding forces more in compare with the conventional fluid and pure water with the MQL system. It is also observed that results with Al_2O_3 nanoparticles with 4% vol. Concentration were found effective than others.

Singh and Rao operated hard turning of AISI 52100 grade steel along with solid lubricants – graphite and molybdenum disulfide of about 2μm average particle size. The influence of graphite and molybdenum disulfide lubrication during the entire process was studied and the obtained results were compared with that of machining in dry cutting environment. It has been observed that in case of machining under graphite and molybdenum disulfide environment cutting forces and surface roughness were reduced and in comparison of graphite and molybdenum disulfide in terms of reduction of cutting forces and surface roughness the best results came with molybdenum disulfide. Thereby obtained results established molybdenum disulfide as a lubricant material superior over that of graphite.

Vasu and Reddy reported the machinability behaviour of Inconel alloy under different cutting environment such as dry, MQL, and Al_2O_3 nanoparticles mixed in vegetable oil. The classification was done on the basis of cutting forces, surface roughness, tool wear, and temperature dissipation. The experiment results help to establish the significant parameters which have greater influence in terms of tool wear, feed rate, and the depth of cut. It has been observed that Al_2O_3 in 6% volume concentration showed the best desire results as compared to other cutting conditions.

Sayuti et al. investigated results during milling operation on aerospace duralumin workpiece. The operation was conducted on vertical milling machine. The experiment carried out with onion-enriched nanofluid based cutting fluid and the results were reflected as improved surface quality and reduced cutting. Under different cutting environment of lubrication the lubrication with highest concentration (1.5 wt%) of carbon onion achieved the minimum cutting force and surface roughness. As per experimental results they were claimed for 21.99% reduction in cutting forces and 46.32% reduction in surface roughness when it compared with the results obtained with normal lubrication oil.

Nam et al. has examined the effect of nanofluids with MQL technique in micro-drilling process using aluminium as a workpiece material. Inclusion of nano diamond (ND) in vegetable oil and paraffin oil has made to prepare nanofluids. During the machining process different types of cooling and lubricating environment were used and those are compressed air (CA) lubrication, base oil along with MQL technique, and nanofluid based MQL. Minimum value of holes through micro-drilling recorded as 87 before tool failure when CA lubrication used. On the other hand it able to made 150 holes without failure in case with normal base oil lubrication and with nanofluid based MQL technique. In this examination, to see the influence of ND particles observation has made and comparison held as per thrust force and drilling torques up to 86 holes. SEM images of drilled holes have taken to observe holes quality. In implementation of CA lubrication burrs were seen around the circumference of drilled hole and left behind the chip in the drilled holes caused for poor quality of holes. Whereas, this problem have not been seen with nanofluid with MQL technique because of their desire ball bearing effect. As per investigation of ND particles 1 vol% of inclusion in paraffin oil and 2 vol% inclusion in the vegetable oil were found more effective in order to bring down the torque and thrust force. However, 1 vol% inclusion of ND particles in paraffin oil is found to achieve lowest force and drilling torque.

Verma et al. investigated that nanoparticles of MoS_2 had outstanding tribological characteristics. encouraged by this, **Shen et al.** applied MoS_2 various MoS_2 combination with base fluids during grinding process of cast iron .it has found that implementation of nanoparticles proved excellent in term of giving reduced tangential grinding forces, frictional forces and normal forces. it has also found that G-Ratio of process also improved.

In order to get lubricating effect of carbon anno tube in grinding process, **Shen and Shih** immersed multi walled carbon nano tubes in a cutting fluid of soybean oil and performed grinding on CBN grinding wheel on ductile iron. It has observed that inclusion of CNT in soybean oil couldn't prove significant in order of reducing the grinding forces. Maximum reduction in temperature and improved surface finish were obtained only with normal flood cooling.

Nam et al. investigated effect of ND particle inclusion on micro drilling process by using paraffin oil and vegetable oil as base cutting fluid under MQL environment. It has observed that inclusion of ND particles found effective in order of giving reduce values of thrust forces and grinding torque. Whereas comparative study shown that paraffin oil based nanofluid found more effective than vegetable oil based cutting.

Sayuti et al. investigated the effect of SiO_2 nanoparticles mixed with coconut oil based cutting fluid in end milling operation. The concentration inclusion of SiO_2 nanoparticles was varied from 0 to 1 %. It has seen that increment of SiO_2 nanoparticles found be effective in order of forming a thin layer over machined surface. This provides ball bearing effect causes for reduction in cutting forces, temperature, and surface roughness of the machined surface.

2.1.2 Effect on surface roughness

Gopal and Rao conducted the experiment using graphite's solid lubricant in grinding of Silicon carbide (SiC). The results show reduction in Tangential cutting force, temperature, surface roughness, and specific energy were found when compared to dry cutting environment. Higher material removal rate and reduced wheel wear also have seen under graphite solid lubrication environment. Hence, grinding under graphite environment proved better in terms of higher productivity and a better product quality.

Khalilpourazary and Meshkat conducted an experiment on hobbing process to see the effect of alumina oxide based nanofluid. In order to get the results nanoparticles were mixed with mineral oil based cutting fluid and the hobbing process performed on DIN1.7131 using different cutting environment. It is observed that when the study was compared, flank and crater wear of the hob tool significantly reduced under aluminium oxide based nanofluid environment along with reduced average surface roughness of It was also found that the average surface roughness of the produced gears under nano lubrication cutting environment.

Mao et al. to investigate the trobological properties of nanofluid conducted grinding operation to get friction and wear mechanism. They were found that nanoparticle based fluid associated with an excellent anti wear characteristics which results in reduced tangential cutting forces and surface roughness.

In order to find out the effect of SiO_2 nanoparticles **Sayuti et al.** has conducted an experiment in term of getting tool wear and surface roughness during turning of AISI 4140 steel. It was found that 0.5% inclusion, 60 º nozzle angles, and air pressure of 2 bar found effective under inclusion of nanoparticle inn term of giving less tool wear. Whereas, 0.5% concentration of nanoparticle with 30º nozzle angle orientation gives best surface finish.

Rahmati et al. investigated the surface morphology using end milling operation with MoS_2 nanoparticles. The experiments were carried out using normal cutting fluid in first mode and using ordinary lubricant as the first mode and MoS_2 nanoparticles dispersed cutting fluid as second mode. It has observed that inclusion of MoS_2 nanoparticles reduce surface roughness by the action of polishing and filling at the machined surface. It has been found that results clearly indicate that 0.5 wt% MoS2 nanoparticle inclusion gives best surface quality. Whereas, further inclusions of nanoparticle causes for decrement in surface quality.

Kwon et al. studied the tribological behaviour of the nanographene additives in different cutting environments such as dry, water soluble oil and vegetable oil. Various tribological tests such as wetting angle measurement, friction tests using a ball-on-disk setup, and MQL ball milling test were conducted under a variable sets of loads and speeds. It was observed that the addition of exfoliated nanographene particles in the cutting fluid successfully improved the wettability and surface finish of the cutting surface. The best cutting performance was exhibited by MQL using 0.1wt % xGnP with 1 μm diameter. However the CBN platelets were found to be more advantageous than nano graphene particles in reducing flank and central wear inspite of having similar friction behaviours.

Saravanakumar et al. has investigated the effect of silver nanoparticle based cutting fluid in turning operation. During the experiment lubricating and cooling properties on silver nanoparticles has observed and comparison has made on the basis of different cutting environment. They were found that beneficial effect of nanoparticle reflects as reduced surface roughness, cutting forces, and cutting temperatures.

Lee et al. investigated an experiment in order to explore the wide application of Al_2O_3 nanoparticles and nano diamond (ND) using micro grinding. It has observed that in term of reducing grinding forces and providing the good surface quality ND particles proved more effective from Al_2O_3 nanoparticles. Whereas, in term of providing reduced surface roughness Al_2O_3 nanoparticles were found more effective.

2.1.3 Effect on cutting temperature

Mao et al. has carried out an experiment in order to investigate the suspension stability of Al_2O_3 nanoparticles with MQL technique in grinding. The found results indicate that Al_2O_3 nanoparticles have got poor suspension stability in short-time ultrasonic vibration. It has claimed that suspension stability of Al_2O_3 nanoparticles can improve by using 0.5% concentration and running the ultrasonic vibrator at least for 1 hour.

Sayuti et al. investigated the effect of SiO_2 nanoparticle mixed with coconut oil based cutting fluid during end milling operation of AISI 6061-T-6 aluminium alloy. To get difference in observation nanoparticles concentration were ranges from 0 to 1%. It has seen that on increasing the concentration of nanoparticles a thin layer of SiO_2 forms in between contact surfaces. It has been noted that this films are generally provides ball bearing effect which helps to reduce the values of cutting forces, lowers down the cutting zone temperature, and enhances the quality of machined surface.

Roy and Ghosh investigated an experiment on AISI 1040 steel during high speed turning and multilayer of cemented carbide inserts the experiment carried out with nanofluid had inclusion of MWCNT. The experiments were observed under three different cutting environment namely: dry, wet condition, and MQL technique of lubrication. They were found that maximum reduction in cutting zone temperature was recorded with nanofluid inclusions which were in the range of 10% to 30%. Also MQL environment was found much better than wet cutting condition in terms of giving performance.

Rao et al. investigated a turning experiment with CNT nanofluid MQL technique to estimate the effect on tool wear and cutting zone temperature using HSS and cemented carbide tool. Different concentration inclusions of CNT were used during machining process using normal water as cutting base fluid. The found results clearly indicated that for the initial few minutes tool wear takes place rapidly, whereas it gets stable when the machining further progresses.

They were found that high cutting zone temperature was associated with carbide tool in comparison with HSS tool under dry cutting environment. Same trend of nodal temperature has seen as that in case of tool wear on increasing the cutting time. Also it is found that temperature decrease with increase in nanoparticles inclusion. Best result was obtained with 2% CNT inclusion. Tool wear rate decreases rapidly up to 2% inclusion of CNT.

Saravanakumar et al. investigated a turning operation carried out with silver nanoparticles with normal cutting fluid. The study was observed on the basis of cooling and lubricating effect under nanofluid and normal cutting fluid to establish a comparison between them. After looking at results they were found that nanofluid inclusion proves its beneficial aspect by giving reduced values of cutting forces, cutting temperature, and with improved surface quality results.

Shen et al. conducted an experiment using Al_2O_3 nanoparticles and ND based cutting fluid with MQL environment to investigate the comparative results with dry and wet lubrication. The experiment was carried out using grinding process of cast iron. It was found that compare to dry and normal cooling machining condition nanofluids environment found better in term of giving reduced grinding forces and improved surface quality also it prevents the burning phenomenon of workpiece by virtue of efficient cooling effect.

Mao et al. investigated the effect of nozzle spraying orientation on the performance when hardened AISI 52100 steel used as work material studied the effect of nozzle spraying direction during surface grinding of hardened AISI 52100 steel using grinding process. It was found that when the air presuusre increases there is reduction on grinding forces, cutting zone temperature, and surface roughness happens. Best result was observed for shorter nozzle.

1.1.4 Effect on tool wear

Gopal and Rao conducted an experiment using solid lubricant of graphite performing grinding of SiC. It has found that cutting temperature along with all another cutting machining characteristics reduces in case of nano graphite inclusion when compared to dry cutting environment thereby increase in G-ratio has also seen as a result of inclusion. Hence, grinding under nano graphite based cutting fluid environment is found effective in order of giving improved productivity and improved surface finish.

Kalita et al. investigated the effect of MoS_2 nanoparticles based with two different cutting fluid namely: soybean oil and paraffin oil used followed by grinding process using steel and cast iron as the as the machining material. From the result it has claimed that inclusion of nanoparticles reduces the frictional losses thereby reduction in tool wear and also reduction in specific energy requirement and increment in G-ration.

Amrita et al. used nano graphite powder based soluble oil cutting fluid to investigate the effect of inclusion during machining of steel with tool insert of cemented carbide. The performance was observed on the basis of cutting forces, flank wear, chip morphology, cutting temperature, and machined surface quality. It has been found that best quality observed with implementation of nanofluid as compare to dry, normal flood cooling and normal MQL cutting environment.

Khandekar et al. conducted experiment to compare the cutting performance and wetability characteristics between 1% inclusion of Al_2O_3 nanoparticles based cutting fluid, normal water and conventional cutting fluid. The experiment was carried out using AISI 4340 steel as work material and uncoated cemented carbide tool. it has found that 1% inclusion of Al_2O_3 nanoparticles found more effective in order of improving wetability characteristics of base fluid. Along with this benefit major reduction in cutting forces, surface roughness, and tool wear has also seen in case of Al_2O_3 nanoparticles base cutting fluid when compared to other machining environments.

Prasad and Srikant carried out experiment which was turning of AISI 1040 steel on lathe machine using HSS and cemented carbide tools. The purpose was to observe the performance of nano graphite immersion in the cutting fluid using MQL technique. It has seen that on increment in concentration of nanoparticles cutting forces, tool wear and surface roughness values decreases. However, for the same cutting condition it is also found as cemented carbide tool performs better than HSS tool in term of giving less value of cutting forces, surface roughness, cutting temperature, and tool wear. On other hand it is also noticed that as floe rate of graphite inclusions increases its results reflected in reduced values temperature and tool wear. Conclusion made as 0.3% nano graphite inclusion with a typical flow rate of 15 mL/min found best as per giving good results.

2.2 Effectiveness of nanofluid lubrication over dry, conventional and MQL technique

Mao et al. investigated the grinding characteristics of AISI 52100 steel to compare the result with dry, wet and normal water MQL techniques. It has found that Al_2O_3 nanoparticles with base fluid as water in presence of MQL technique performs very well in terms of giving results as reduction in grinding force, temperature, improvement in surface quality in comparison ordinary MQL grinding process. The nanoparticles comes with ball bearing effect to serve better performance

Sayuti et al. investigated results during milling operation on aerospace duralumin workpiece. The operation was conducted on vertical milling machine. The experiment carried out with onion-enriched nanofluid based cutting fluid and the results were reflected as improved surface quality and reduced cutting. Under different cutting environment of lubrication the lubrication with highest concentration (1.5 wt%) of carbon onion achieved the minimum cutting force and surface roughness. As per experimental results they were claimed for 21.99% reduction in cutting forces and 46.32% reduction in surface roughness when it compared with the results obtained with normal lubrication oil.

Prabhu and Vinayagam conducted experiment to see the effect of surface generation inn gridding process using CNT. . Four different lubrication conditions were use namely: dry, water-soluble-oil, SAE20W40 cutting oil, and MWCNT based nanofluid. From the results it has found that surface roughness varied as 0.251 mm, 0.137 mm, 0.096 mm, and 0.057 for the corresponding lubricating conditions respectively. From the result observation it can be easily seen that novelty of nanoparticles inclusion performs as per its characteristics.

Rahmati et al. carried out experiment using different concentration of MoS_2 nanoparticles base cutting fluid to have a comparative study among them. The end milling machining was done on the AL6061-T6 aluminium alloy effect of different MQL parameters such as nozzle angle, air pressure, and nanoparticles concentration on the different machining parameters such as cutting force, cutting zone temperature, and surface roughness was noticed. It has seen noted that the lowest value of cutting forces were obtained with 1 % nanoparticles concentration inclusion, whereas lowest value of cutting temperature and surface roughness was associated with 0.5% nanoparticles concentration inclusion. When it came to nozzle orientation it was found that 30 º nozzle angle positions has got lowest value of cutting forces along with lowest cutting zone temperature. On the other hand 60º nozzle angle position was found to be effective in order to achieve least value of surface roughness.

CHAPTER 3

OBJECTIVE

After having the brief idea about influence of nanoparticles in the machining processes from the past literatures, it has been concluded that inclusion of nanoparticles in the cutting fluid always proved beneficial as per providing improved performance for the machining processes, this is due to its remarkable cooling and lubricating effects. However, number of paper have been seen on addition of Al_2O_3 nanoparticles in the cutting fluid and it is considered as a most preferable technique, even though wide range of benefits of using Al_2O_3 nanoparticles is not over yet. In order to explore hidden qualities and the benefits of Al_2O_3 nanoparticles current research work has been conducted. In the Current study Al_2O_3 particles of about size in the range of nanometre (<50nm) has been taken to prepare nanofluid and water-soluble-oil stands for base fluid. MQL cooling and lubricating technique employed for the turning process. Investigation progressed for different lubricating conditions, namely: traditional MQL technique, MQL with Al_2O_3 nanoparticles inclusions. The experiment was carried out for two different running mode conditions: finishing mode and roughing mode for machining of 17-4 PH stainless steel using turning operation. Machining parameters (cutting speed, feed, and depth of cut) were varied as per running condition. Therefore, the current study has been designed and undertaken with the following major objectives:

- To investigate the influence of Al_2O_3 based nanoparticles on the following characteristics of 17-4 PH stainless steel, an aeroengineering alloy:

    1. Cutting forces
    2. Coefficient of friction
    3. Cutting temperature
    4. Tool wear
    5. Chip reduction coefficient

6. Surface roughness
7. Chip morphology

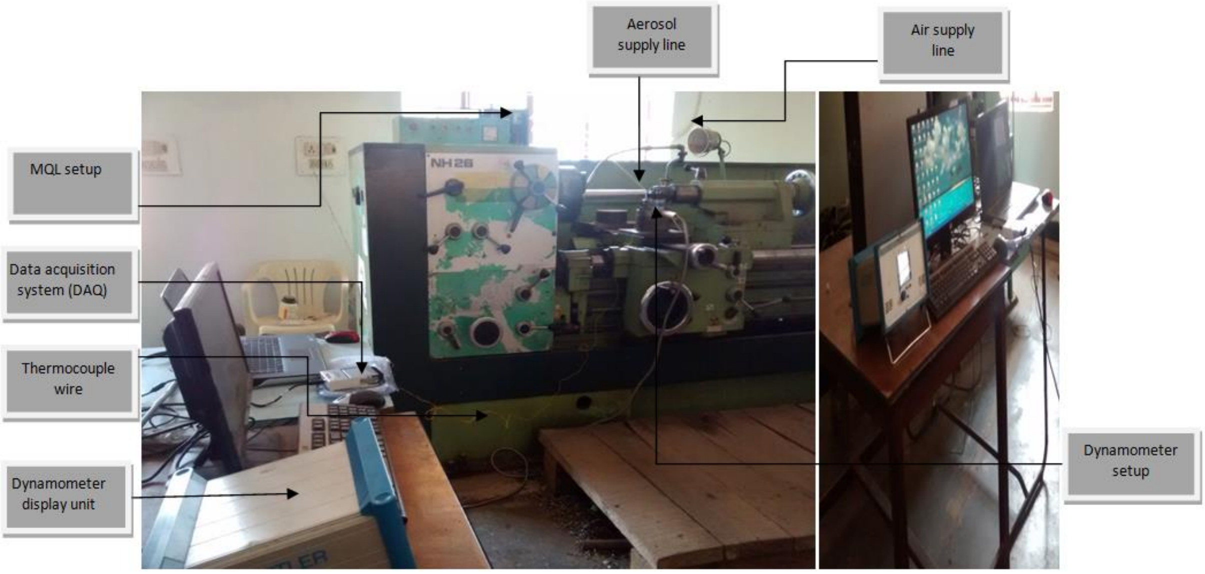
- To compare the result of nanofluid lubrication with that of results of conventional flood cooling as well as with MQL (without additives).

Chapter-4

EXPERIMENTAL PROCEDURE

4.1 Experimental setup

The experiment is carried out on a cylindrical job of 17-4 PH stainless steel. The initial diameter of the workpiece was 80mm and length was 600mm. All the machining performances were conducted on a heavy duty lathe machine fig. 1**.**



(a) (b)

Fig. 1: (a) whole experimental setup, and experimental setup for force and temperature related data (b)

All the machining process is carried out along with minimum quantity lubrication technique. The MQL flow rate through nozzle was set to 20 ml/h. Air pressure was set to 6 bar. Nozzle distance was 40 mm from the cutting edge of tool at an angle of 15^{o} from the longitudinal axis of job (fig. 8). The diameter of used nozzle was of about 2 mm. The setup for MQL unit has shown in fig. 3.

Fig. 2: Data acquisition system (DAQ)

Fig. 2 shows DAQ unit used for cutting zone temperature measurement. Experiment conducted with using K-type thermocouple containing chromium and aluminum wire. One junction of thermocouple attached to cutting tool and another one was attached with DAQ unit.

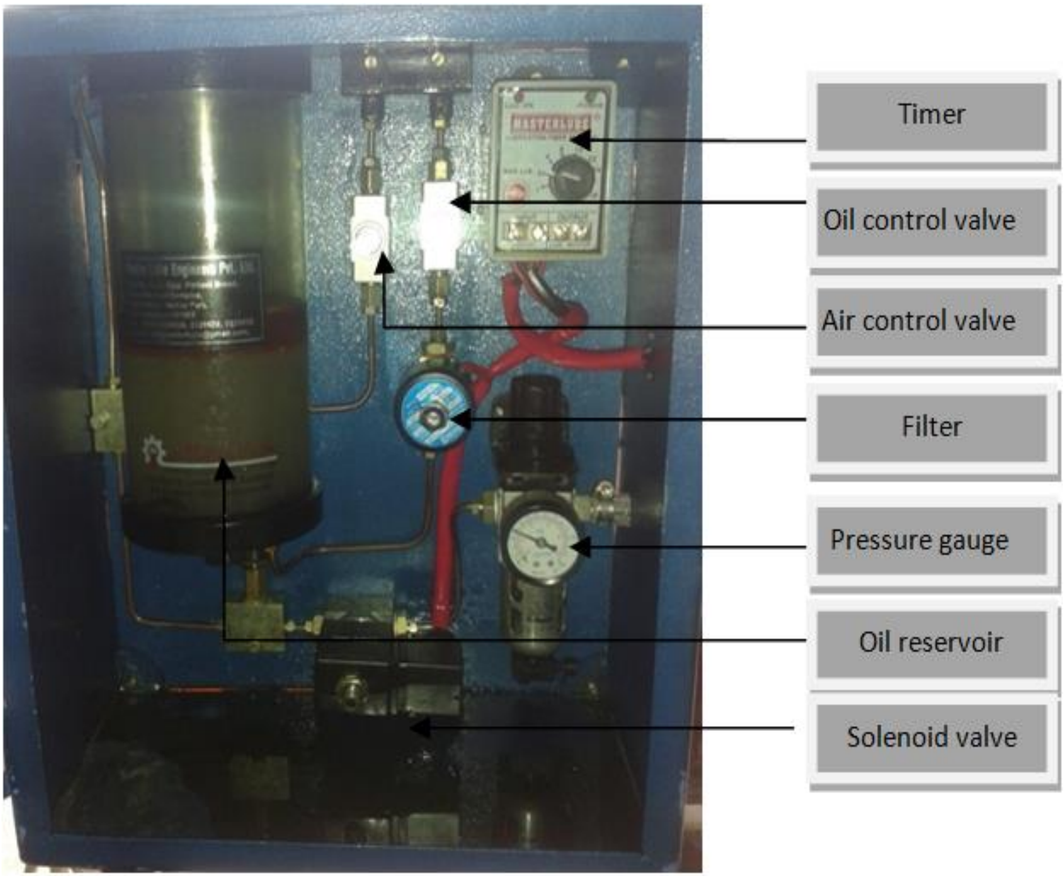


Fig. 3: Minimum quantity lubrication (MQL) setup unit

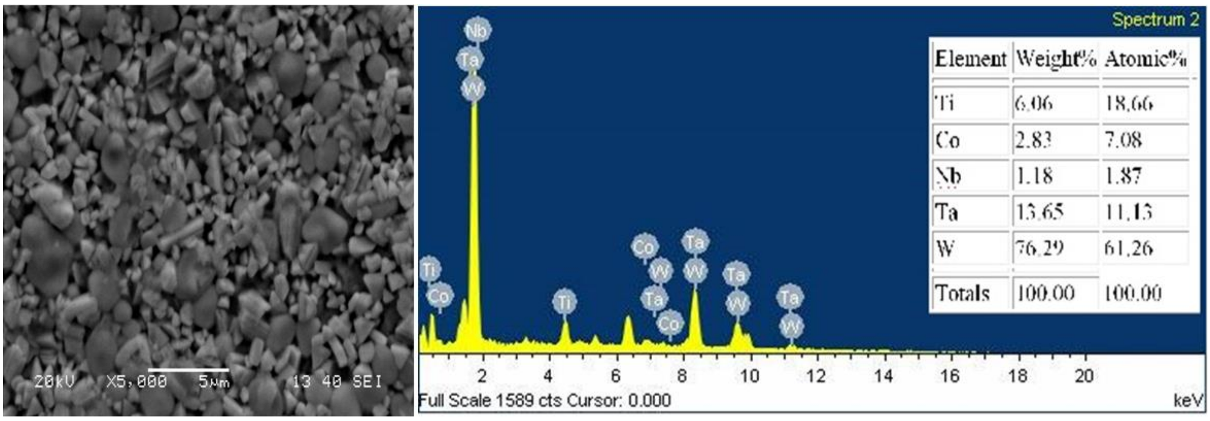
4.2 Selection of workpiece and tool material

The experiments were performed on 17-4 PH stainless steel also known as Type 630 stainless steel. The chemical composition of which has shown in Table 1.

Table 1: Chemical composition of 17-4 PH stainless steel

Elements	C	Mn	Si	P	S	Cr	Ni	Cu	Nb+Ta
Wt %	0.07	1.0	1.0	0.04	0.03	15.0-17.0	3.0-5.0	3.0-5.0	0.15-0.45

In the machining uncoated cemented carbide tool insert (Make: Widia, India) was used which has designation as P30 grade and SCMT 120408. Whose composition contained WC, TaC, TiC, Co, and NbC. Fig. 4 shows SEM image of fresh cutting tool along with EDS spectrum.



(a) (b)

Fig. 4: (a) Surface morphology and (b) EDS spectrum along with chemical composition of as-received cemented carbide insert

4.3 Selection of cutting environment

The experiments were performed under two different running conditions, carried out in minimum quantity lubrication (MQL) environment with variation in nanoparticles concentrations. Conventional cutting oil used as the base fluid for all the conditions. Concentration of nanoparticles inclusion varied under both the running conditions to establish the comparative study among them on the basis of variation in machinability characteristics. Aluminium oxide nanoparticles (supplier: Sigma Aldrich, China product) has taken to prepare nanofluids which has to be applied on to the cutting zone. The properties of Aluminium oxide are exposed in Table 2. The Field emission scanning electron microscopy (FESEM) images of Al_2O_3 nanoparticles have taken to understand the shape, size and distribution, which have shown in Fig. 6 (a) and Fig. 6 (b). Al_2O_3 particles were mixed with the base fluid thoroughly with the help of ultrasonic cleaner machine (fig. 5, supplier: Adarsh enterprise) to minimize the chances of particle settlement at the base and to maintain proper suspension behavior of it. Fig.4 shows the ultrasonic cleaner machine loaded with cutting fluid which is operated for 1 hour. Four different types of MQL environments were used for investigation and those are:

1. Conventional cutting fluid
2. Conventional cutting fluid with 2 vol% inclusion of Al_2O_3 nanoparticles
3. Conventional cutting fluid with 5 vol% inclusion of Al_2O_3 nanoparticles
4. Conventional cutting fluid with 8 vol% inclusion of Al_2O_3 nanoparticles

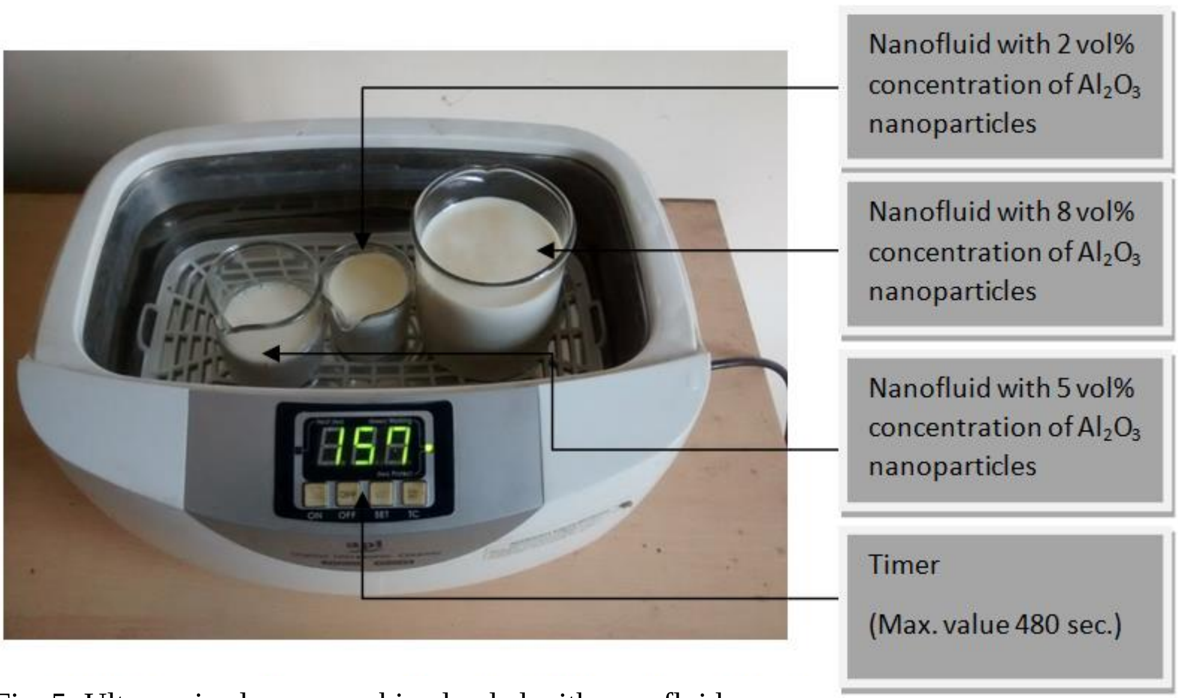
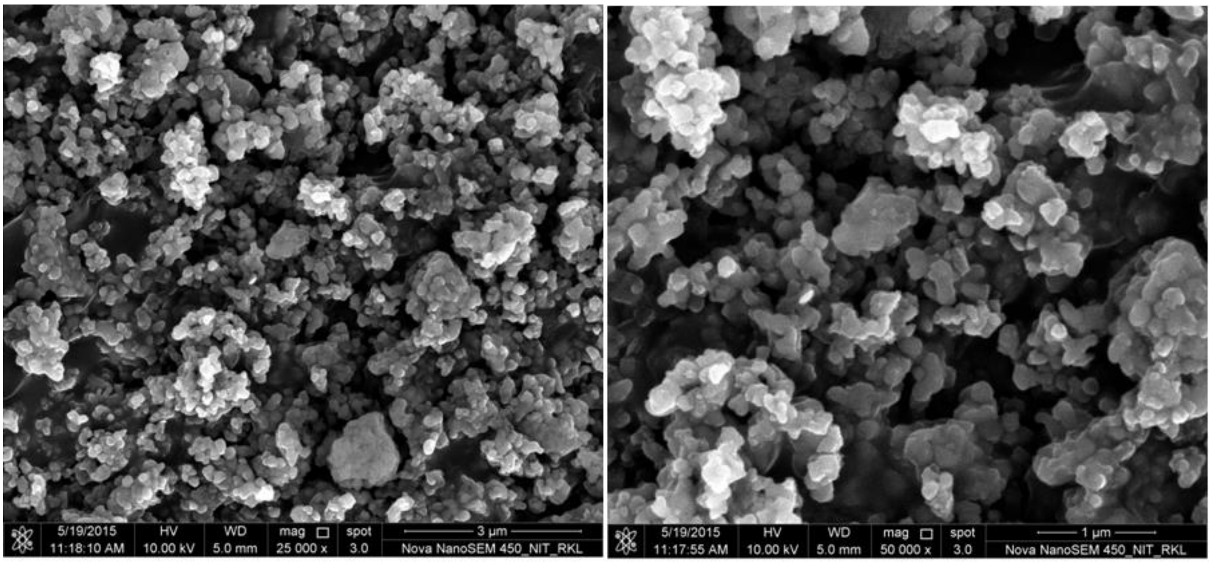


Fig. 5: Ultrasonic cleaner machine loaded with nanofluid

Table 2: Properties of Aluminium oxide (Al_2O_3)

Molecular formula	Al_2O_3
Molar mass	101.96 g/mol
Appearance	White solid
Density	3.95 g/cm^3
Melting point	2072°C
Solubility in water	Insoluble
Crystal structure	Various
Particle size	<50 nm (avg. size)



(a) (b)

Fig. 6: FESEM images showing the surface morphology of Al_2O_3 nanoparticle at magnification of (a) x25000 and (b) x50000

4.4 Eexperimental Methodology

The machining was carried out using two different running mode conditions, first one is finishing mode and second one is roughing mode in order to have comparative study between them. Under finishing mode cutting condition the machining parameters was kept constant as cutting speed=158 m/min, feed=0.1 mm/rev, and depth of cut=0.5 mm., on the other hand under roughing mode cutting condition these values are changed as cutting speed=72 m/min, feed=0.2 mm/rev, and depth of cut=1.5 mm. Concentration of Al_2O_3 nanoparticles varied as 2 vol%, 5 vol%, and 8 vol% for the both running conditions in order to get comparatively study among all of them. In each run of running mode, machining was carried out for 60 sec. and the same run is repeated for 360 sec. After final run of each combination surface roughness were measured using Surface Profiliometer (fig. 7, make: Taylor Hobson: Surtronic 3).

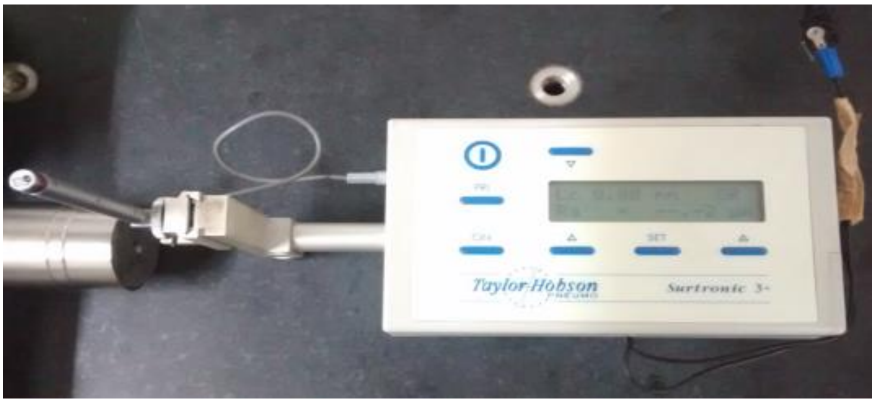


Fig.7: 2D Surface Profilometer (Talysurf)

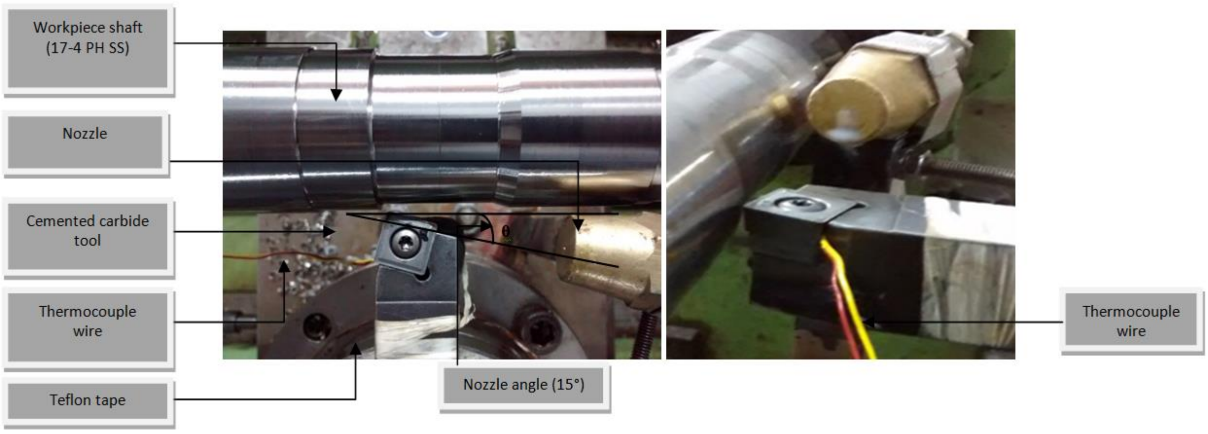


Fig. 8: Close up view of tool, workpiece, and nozzle setup under stationary condition

Table 3: Running mode conditions for the experiment

Finishing Mode	Roughing Mode
V_c-158 m/min	V_c-72 m/min
f-0.1 mm/rev	f-0.2 mm/rev
a_p-0.5 mm	a_p-1.5 mm

During the machining processes output response of the machining in the form of cutting forces and cutting temperature has observed. To measure the cutting forces piezoelectric dynamometer (make: Kistler Instrument Corporation) were used and to find the trend variation in cutting forces data accusation system has been used. The temperature measurement was done with the help of thermocouple. The hot junction of the thermocouple was attached in between of tool and tool holder and epoxy resin were used to keep the tool holder and workpiece insulated from the other parts of machine. The cold junction of the thermocouple was attached with temperature measuring device. Fig. 6 is the DAQ system for measuring temperature.

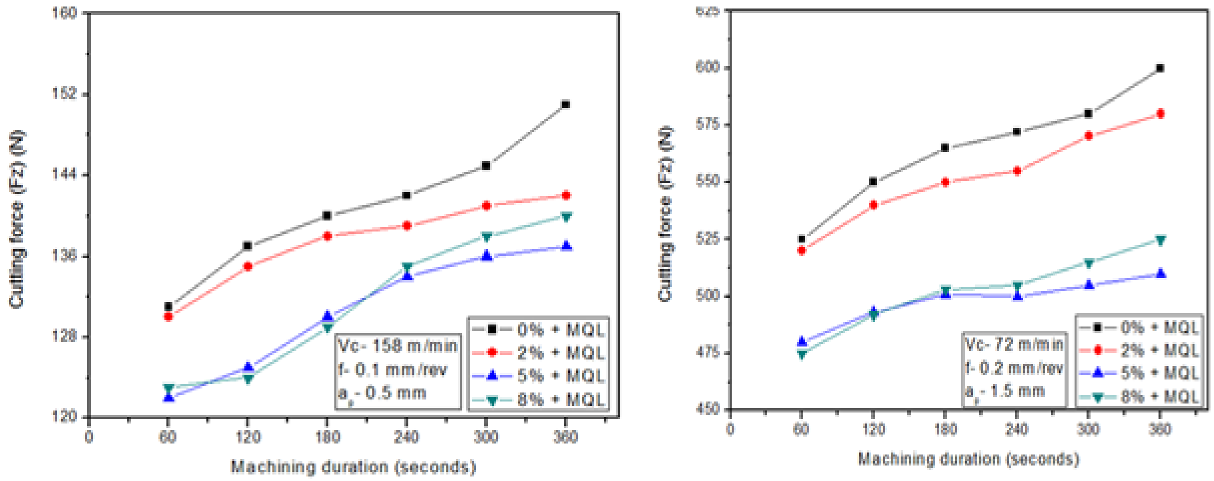
CHAPTER 5

RESULTS AND DISCUSSION

The aim of this experiment was to investigate the effect of different concentrations of Al_2O_3 nanoparticles on the different machinability characteristics under two different running mode conditions. Obtained results were closely observed and it is found that inclusion of nanoparticles up to a certain limit proved to be effective.

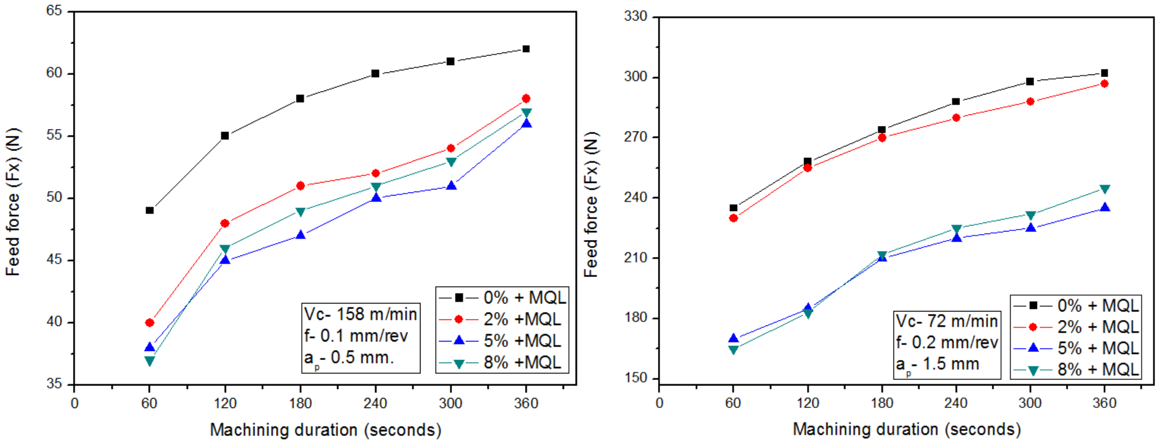
5.1 Effect on cutting forces

At the beginning of the machining process it has generally seen that cutting forces comes with its lower values, this is due to sharp edge effect of cutting tool and as the machining progressed after several minutes cutting tool starts losing its sharpening effect in form of chipping or deformation, which causes for sudden increase in cutting forces values.



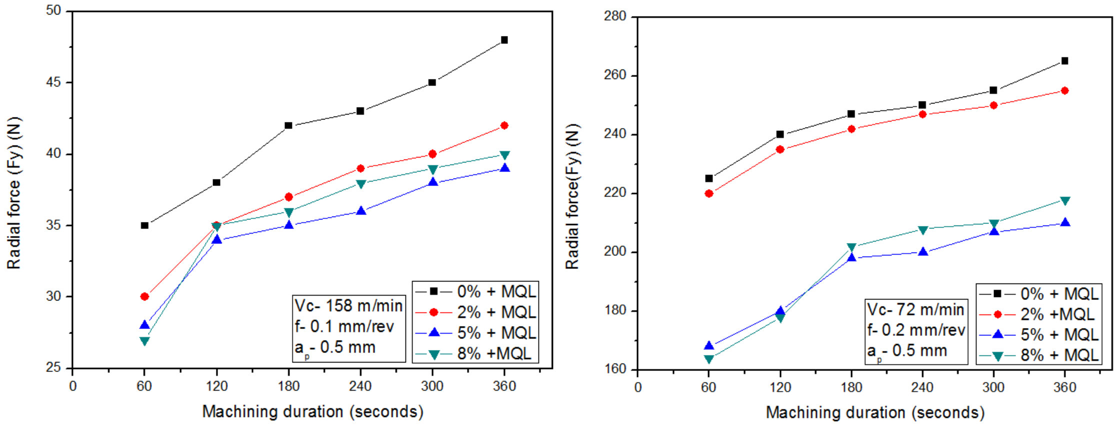
(a) (b)

Fig. 9: Graphs shows variation of cutting force (Fz) for different lubrication environment with respect to cutting time under (a) finishing mode cutting condition, (b) roughing mode cutting condition



(a) (b)

Fig. 10: : Graphs shows variation of feed force (Fx) for different lubrication environment with respect to cutting time under (a) finishing mode cutting condition, (b) roughing mode cutting condition



(a) (b)

Fig. 11: Graphs shows variation of radial force (Fy) for different lubrication environment with respect to cutting time under (a) finishing mode cutting condition, (b) roughing mode cutting condition

Fig. 9 shows main cutting force variation under different lubricating environment whereas, fig. 10 and fig. 11 shows variation in feed force and radial force respectively. Increase in cutting force can be clearly seen for all the conditions as the machining time spent. It is due to possible effect of tool wear. As the machining time increases tool wear take place gradually. This leads the process to experience rapid increase in cutting forces. Thermal softening effect of cutting edge is the main culprit for rapid wear of the tool. From the graph benefit of Al_2O_3 nanoparticles inclusion in the cutting fluid can be justify in terms of getting reduced values of cutting forces as compared to normal MQL technique of lubrication. It is due to outstanding thermal conducting property of Al_2O_3 nanoparticles and its lubricating effects when it comes to nano range. From the graph it can be observed that as the concentration of Al_2O_3 nanoparticles in the cutting fluid increasing its results reflecting in lower values of cutting forces. However, after 5 vol % concentration inclusion of nanoparticles further more inclusion again increasing the force values. As from the graph it is clearly visible that for 8 vol% concentration after initials few minutes cutting force values again increasing. For the initial few minutes 8 vol% proves itself best but after few more minutes its beneficial effect vanishes. To understand this point we can take 5 vol% inclusions as a saturation limit. Any further inclusion will cause for restriction in free flow of nanoparticles. As the machining started after few minutes less wear rate take place and also less value of chip thickness (t_1) obtained with small groves in them due to which it becomes easier for particles to come out from the small opening, and due to more inclusion of Al_2O_3 nanoparticles heat dissipation rate of process also increases which protect the cutting edge from the thermal softening effect, thereby results reflected in lower values of forces. On the other hand, at high wear rate condition rougher surface and increased values of chip thickness (t_2) obtained because of that ability to escape from small opening for 8 vol% concentrations of Al_2O_3 nanoparticles becomes difficult. This causes for again increase in cutting forces. Fig. 12 has been drawn to clarify the involving mechanism behind reduction in cutting forces.

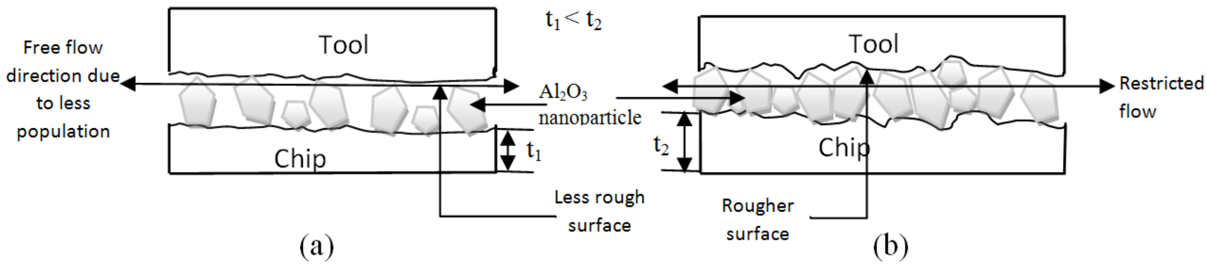
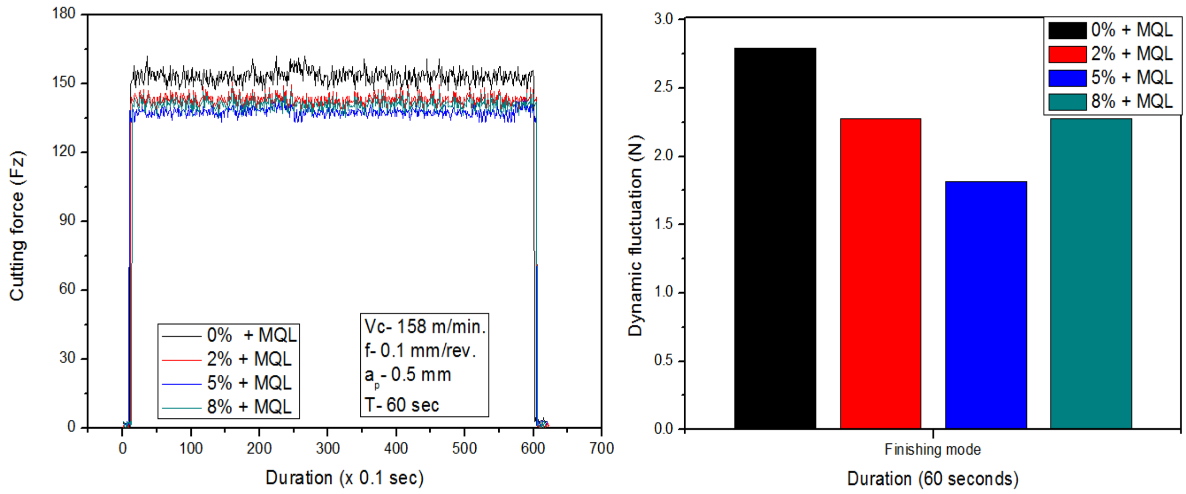


Fig. 12: Condition of nanoparticles flow between tool-chip interface in (a) 5 vol% concentrations, and (b) 8 vol% concentrations of Al_2O_3 nanoparticles in cutting fluid

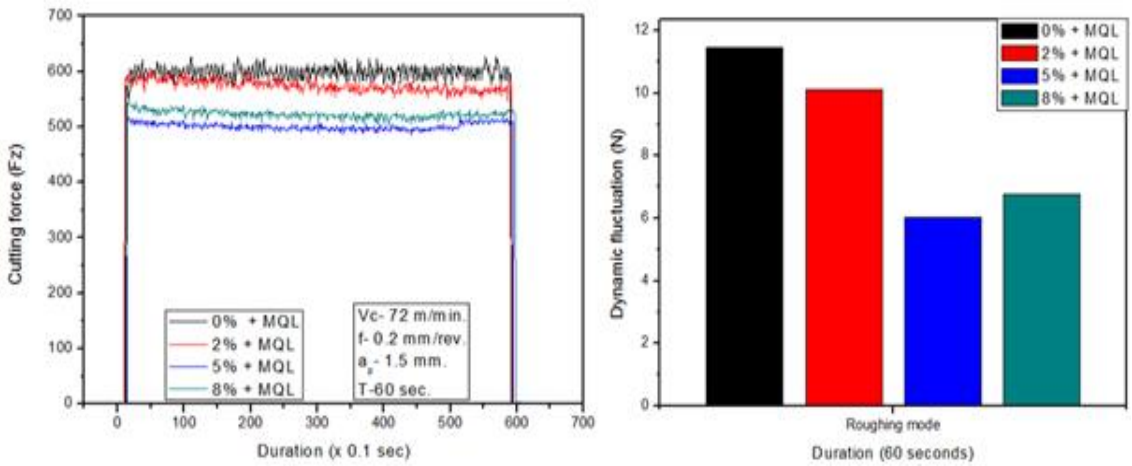
Due to vibrating condition of operating machine and unevenness behavior of work surface and cutting tool edge it is never possible to get a constant force value in practical condition.

However, it has been seen that inclusion of nanoparticles helps to lower down this fluctuation by virtue of its micro-damping property.

5.2 Effect on dynamic fluctuation of cutting forces



(a)



(b)

Fig. 13: Actual variation of cutting force obtained with data acquisition system and dynamic fluctuation using different modes of MQL under (a) finishing and (b) roughing modes at the machining interval of 300 to 360 s.

From the obtained graph (fig. 13(a) and 13(b))for cutting force and corresponds bar chart represents dynamic fluctuation in the cutting force it can be clearly observed that on increase in Al_2O_3 nanoparticles concentration cutting forces values decreases and also dynamic fluctuation rate reducing corresponding to nanoparticles concentration. This effect is a result of micro-damping property of generated nanopaticles fluid film. Due to dissimilar size nanoparticles comes with cushion effects by absorbing sudden load it lowers down the fluctuation of cutting force as the results is clearly reflected in the bar chat for dynamic fluctuation values Fig. 14 is almost able to define micro-damping effect of nanoparticles. Results indicates that due to saturate concentration value of 5 vol% concentration of nanoparticles there is enough space for nanoparticles to flow thereby more cushion effect, whereas in case of due to increase population of Al_2O_3 nanoparticles as in case of 8 vol% concentration flow is not easily possible, thereby less cushion effect.

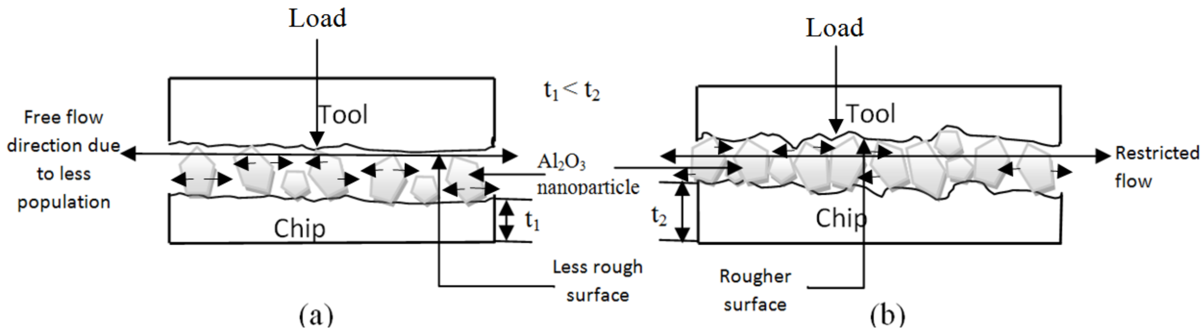
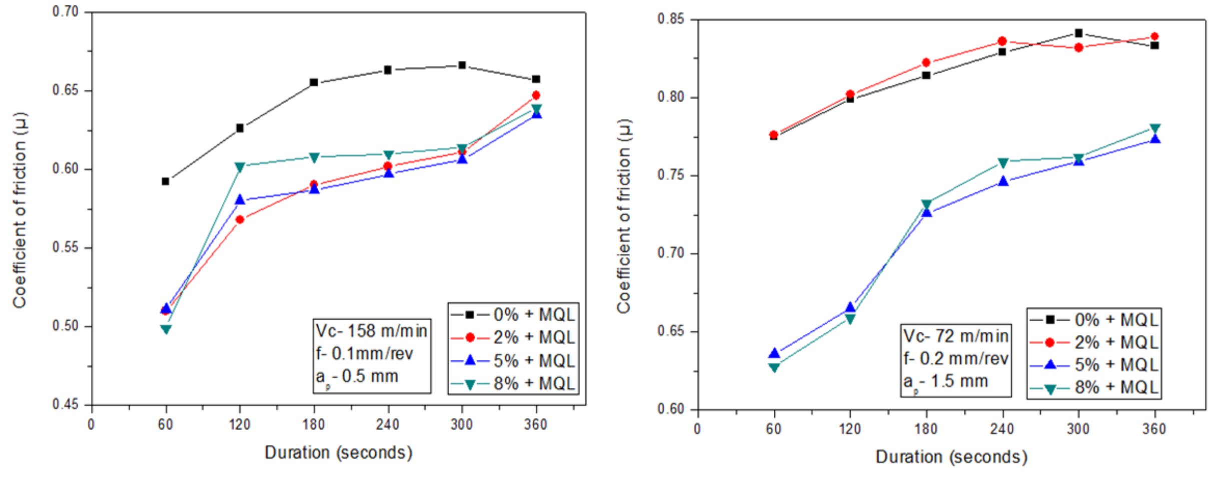


Fig. 14: Micro-damping effect on inclusion of Al_2O_3 nanoparticles under (a) 5 vol% concentration and (b) 8 vol% concentration

5.3 Effect on coefficient of friction (μ)

Coefficient of friction is one of the important factors during any machining process. Its larger values cause for rapid tool wear. Friction coefficient mainly dependent on the nature of surface, high values of roughness leads to higher values of friction coefficient. General formula to calculate friction coefficient are as follows:

$$\mu = \frac{F_z \sin\alpha + F_t \cos\alpha}{F_z \cos\alpha + F_t \sin\alpha}$$



(a) (b)

Fig. 15: Graphs shows variation of coefficient of friction under (a) finishing mode and (b) roughing mode running conditions

Coefficient of friction is a property of surface nature. As the machining time increases rate of tool wear also increases thereby surface quality of tool decreases. Most of the researchers have shown that under any machining condition coefficient of friction is a function of time for the tool. Its value increases as the machining process progresses, graphs 15(a) and 15(b) are evidence of this investigation. As we can see the values of coefficient of friction under both the running conditions are in increasing order, it is increasing as the machining tie increases. This indicates the straight forward results of tool wear. Rough surface of tool on rake face makes flow of chip difficult over it, thereby restricted flow of chip causes tool to experience high stress-strain condition which further causes for increase in cutting forces. In order to overcome this problem addition of Al_2O_3 nanoparticles has made to reduce the area of contact between tool-chip interfaces thereby reduction in coefficient of friction. As Al_2O_3 particles works in the nano range it comes with property of nanoparticles. Rolling effect is one of them properties (fig. 16). This effect causes for reduction in contact surface and rolling action of chip instead of sliding action over tool face. Reduce surface contact and ease flow of chip helps to decrease friction coefficient by virtue of less wear face.

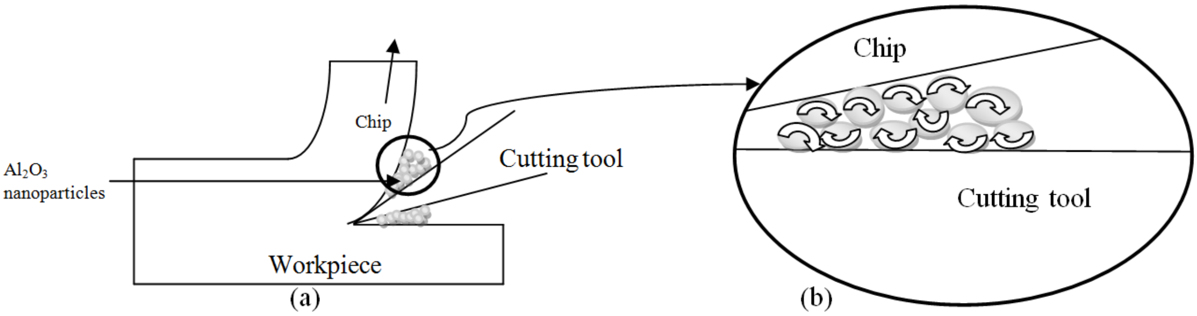
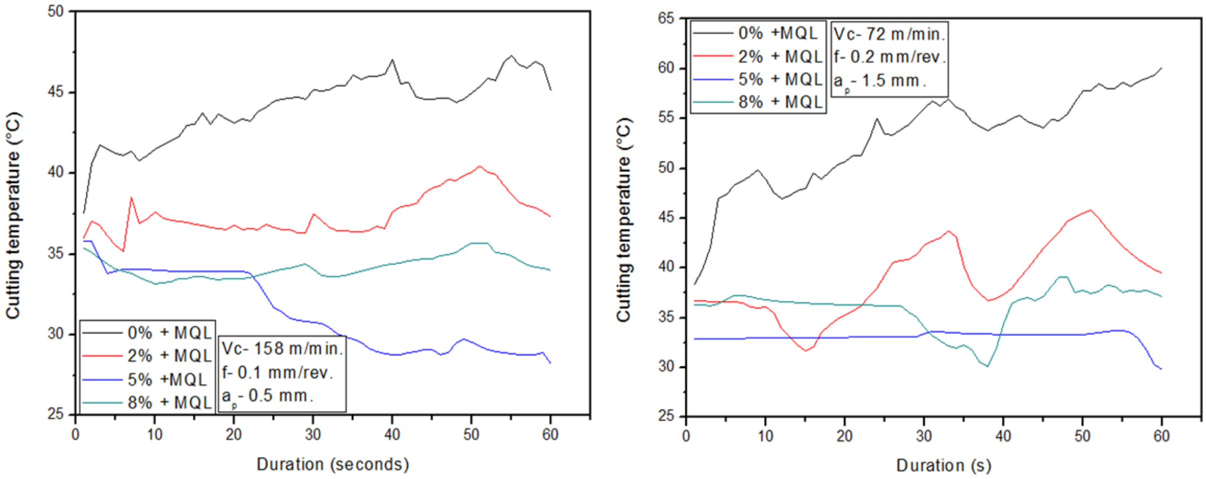


Fig.16: Rolling effect in the presence of Al_2O_3 nanoparticles (a) and (b) magnified view

But as from graph it can be observed that after 5 vol% inclusion of nanoparticles any further inclusion increases the coefficient value this id due to increase in area of contact and restriction to free flow of nanoparticles.

5.4 Effect on cutting temperature

Any machining process is highly dependent on its cutting zone temperature behavior. As it has already been discussed that undesirable elevated temperature causes for rapid deformation of cutting edges thereby failure of tool. So it becomes necessary to limit the cutting temperature value within the safe zone as per tool point of view. However, during any machining process controlling of temperature is not an easy task. To overcome this problem inclusion of nanoparticles has generally made because thermal conductivity of nanoparticles lies above to water and soluble-oil which helps to increase the heat dissipation rate from the tool and workpiece. If temperature dissipation will not made effectively it will also results in poor surface quality of the machined surface.



(a) (b)

Fig. 17: Effect of nanoparticles inclusion on cutting temperature during 360th seconds run for (a) finishing mode, (b) roughing mode running conditions

From the above graphs (17(a) and 17(b)) effect of Al_2O_3 nanoparticles can be clearly identify. For the normal MQL technique it can be clearly seen that as the machining progresses value of cutting zone temperature also increases. Also the above graphs justifies the cooling effect of Al_2O_3 nanoparticles by showing lower values of cutting temperature in comparison to normal MQL lubricating technique. It has summarized that inclusion of Al_2O_3 nanoparticles inclusions proves effective in term of reducing temperature. However, this effect has not be effectively seen in case of 8 vol% inclusion of Al_2O_3 nanoparticles. This phenomenon is also a result of restricted flow of nanoparticles as more population of nanoparticles not able to made escape easily heat dissipation rate also deceases, whereas, due to more number of nanoparticles density in between tool-chip and tool-work interface able to give effective results in comparison with 2 vol% inclusion, this is due to number of particles participates at a time in heat removing process.

5.5 Effect on tool wear

For any machining process to remain effective it is necessary that cutting tool should server for longer time. As changing of cutting tool cost is also considered in one of the major cost of production due to its high precision geometry. Under normal machining condition it has been seen that growth of tool wear rapidly takes place due to presence of high friction between tool-chip and tool-workpiece interface.

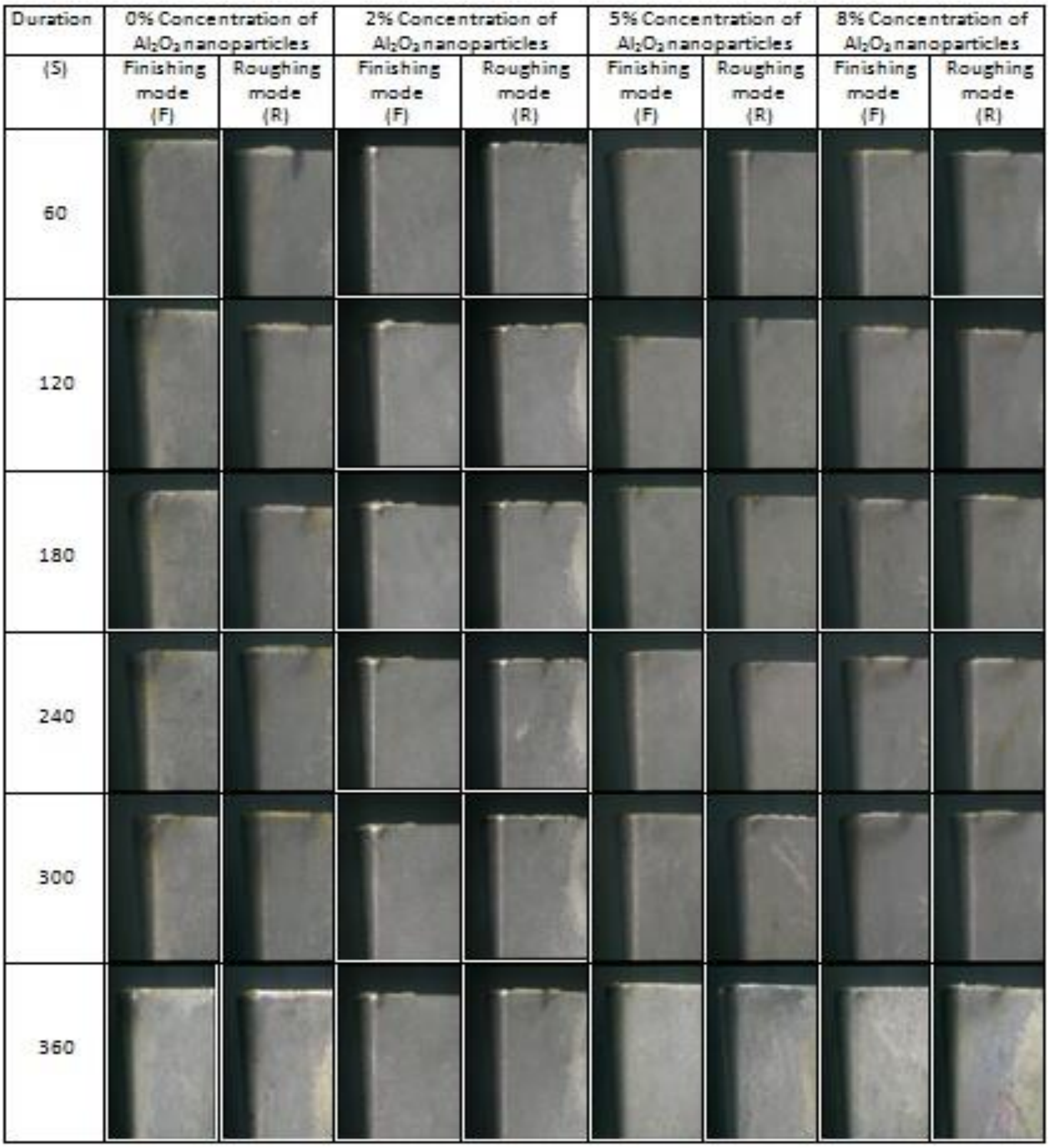


Fig. 18: Growth of wear on flank face for different cutting environment

Fig. 18 shows the growth of flank wear corresponding to cutting environment for different tool. It has been clearly seen that on increment in cutting time flank wear also take place in increasing order.

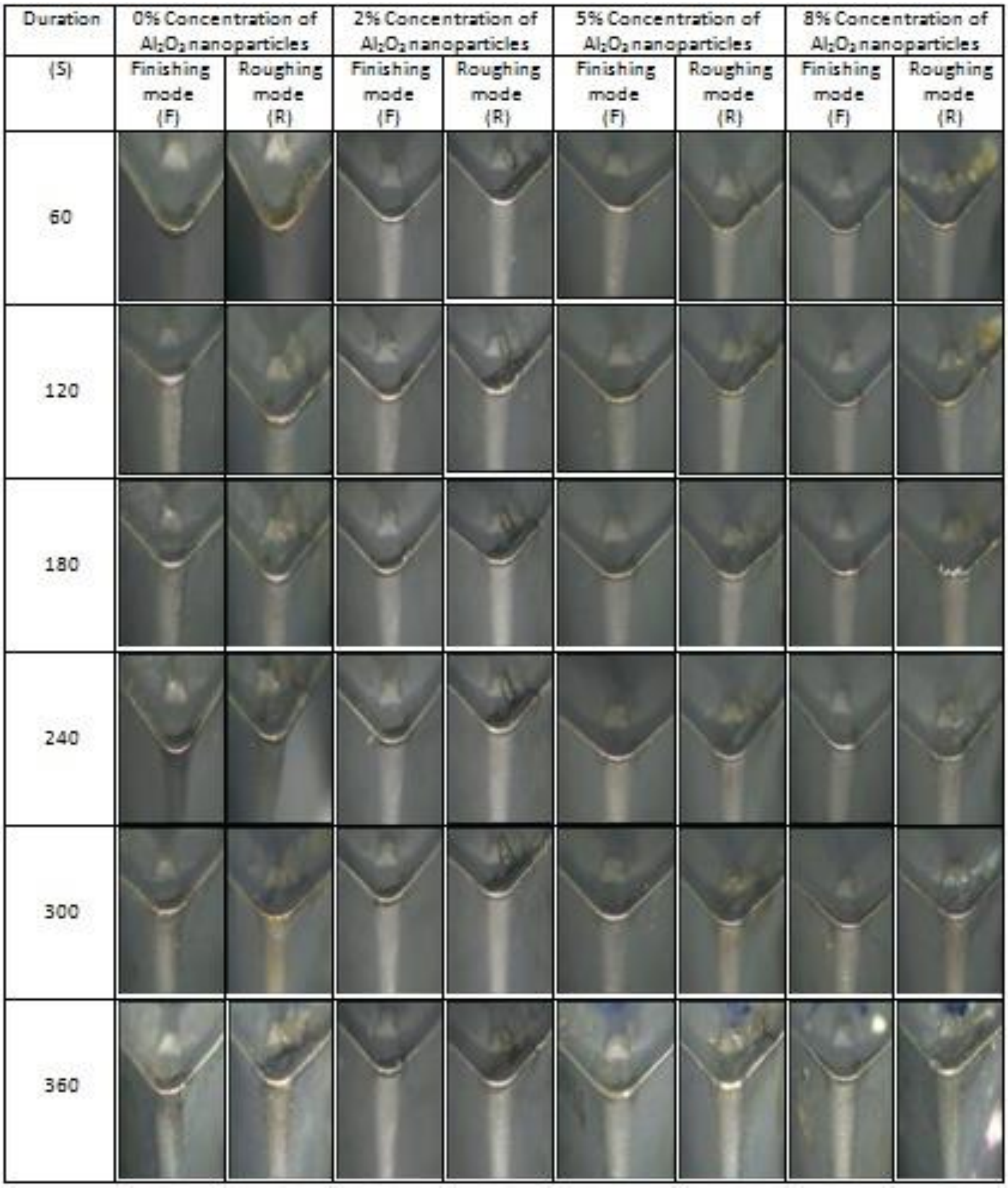
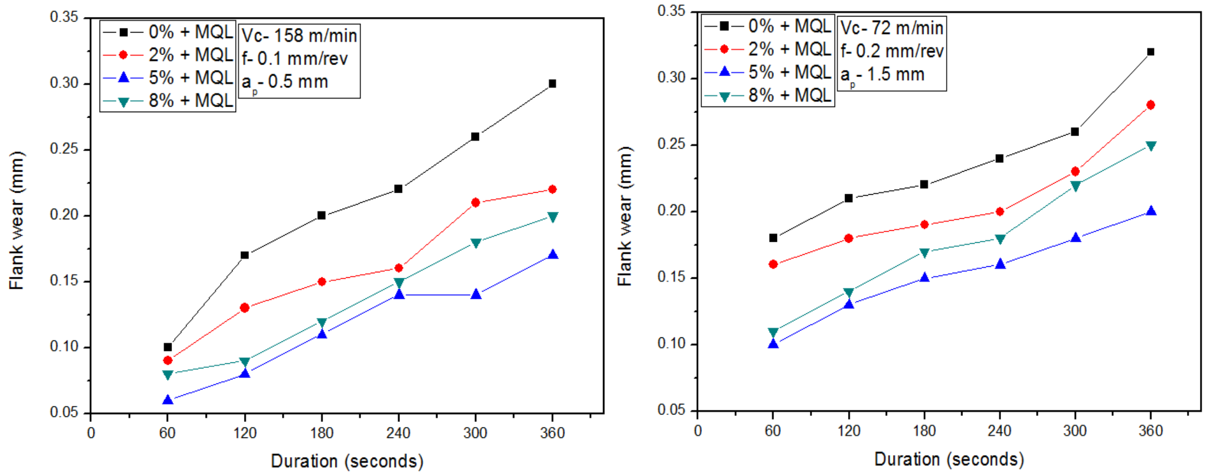


Fig. 19: 3D view of cutting tool after different machining intervals and under different modes of MQL



(a) (b)

Fig. 20: Effect of nanoparticles inclusion on flank wear along with flank wear images after 360th seconds of run for (a) finishing mode and (b) roughing mode conditions

The above two graphs 20 (a) and 20 (b) shows the variation of cutting forces under normal and nanoparticles included cutting conditions. Beneficial aspects of Al_2O_3 nanoparticles can be easily understand after seeing the nature of graph under different cutting environment. As in case of normal MQL due to absence of nanoparticles large amount of tool wear take place in comparisons to other lubricating techniques. Whereas, 5 vol% concentration of Al_2O_3 nanoparticles gives best result in terms of reduced flank wear by virtue of reduced area of contact and proper distribution of load in between the tool-work interface.

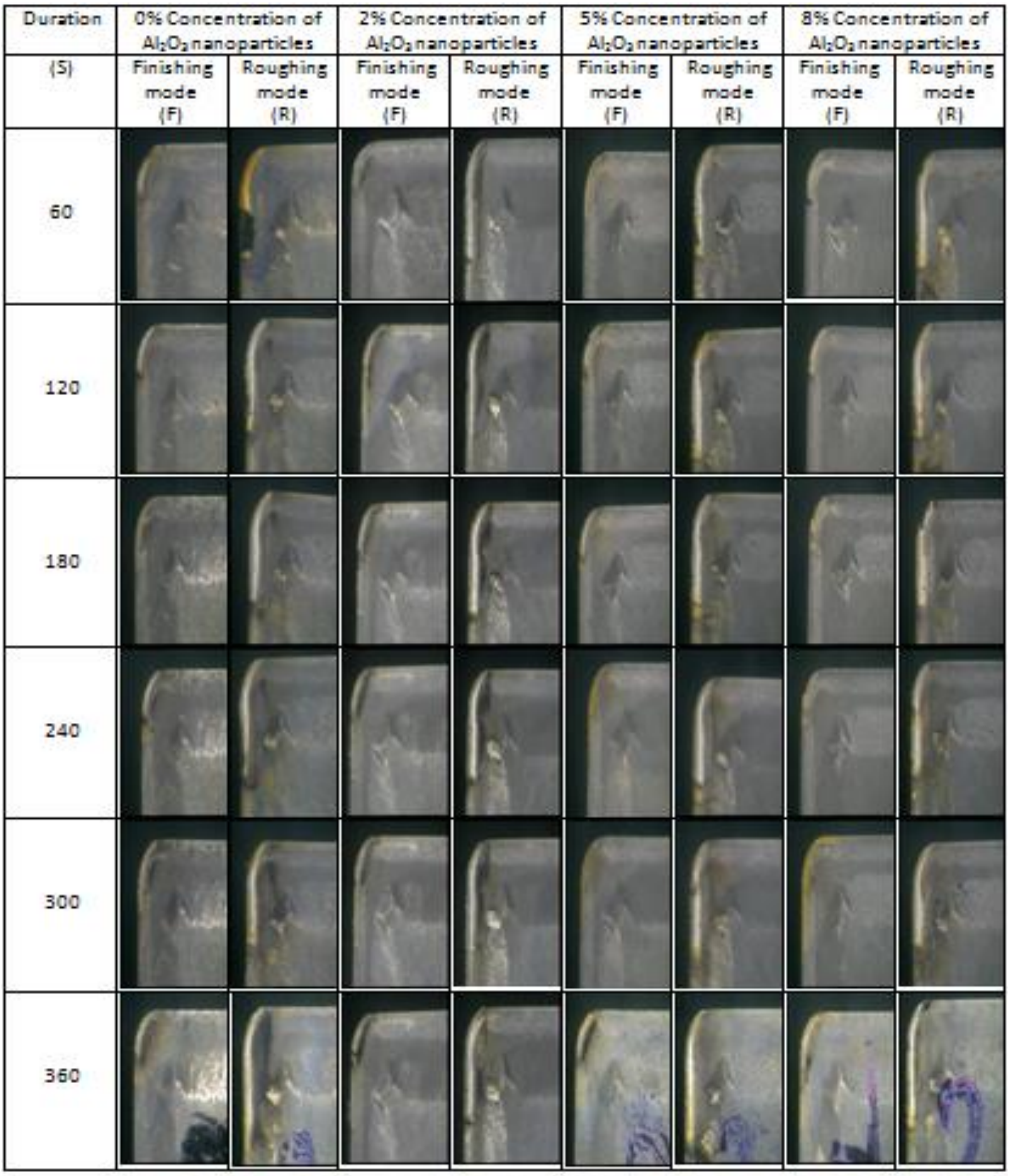
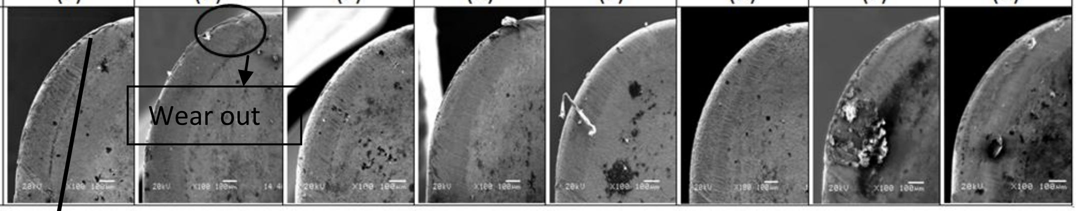
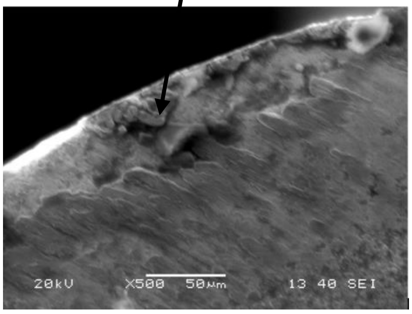


Fig. 21: Growth of crater wear on rake surface

Fig. 21 explains that crater wear also depends on machining time, as we can see that wear on rake surface clearly on increasing order as the machining time has spent.

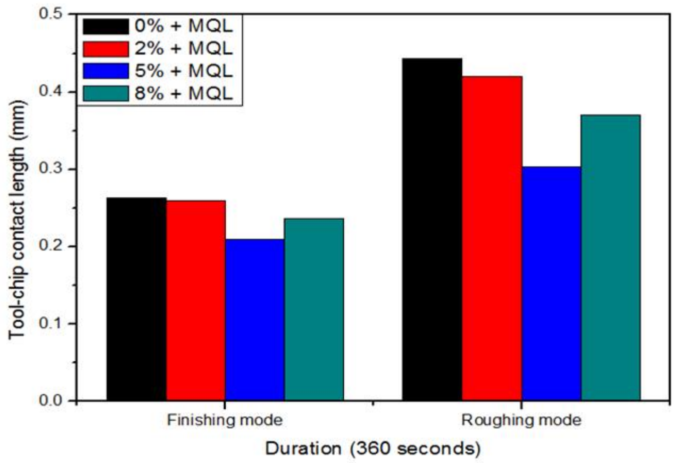
Magnifications	0% Concentration of Al_2O_3 nanoparticles		2% Concentration of Al_2O_3 nanoparticles		5% Concentration of Al_2O_3 nanoparticles		8% Concentration of Al_2O_3 nanoparticles	
	Finishing mode (F)	Roughing mode (R)	Finishing mode (F)	Roughing mode (R)	Finishing mode (F)	Roughing mode (R)	Finishing mode (F)	Roughing mode (R)
X100								

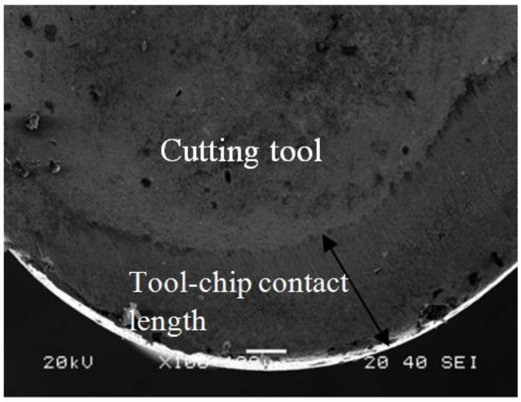
(a)



(b)

Fig. 22: (a) SEM images showing crater wear of cutting tool and (b) magnified view of crater wear for 0 vol% concentration under roughing mode condition showing tool edge chipping





(a) (b)

Fig. 23: (a) Tool-chip contact length over rake surface under finishing and roughing condition (b) cutting tool showing tool-chip contact length

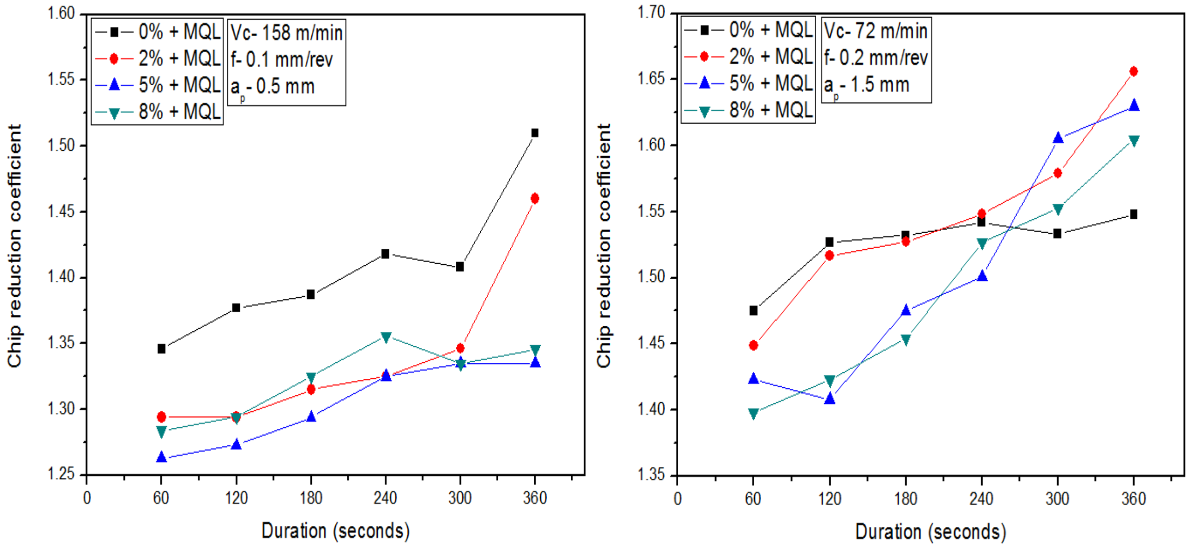
From the image 22 (a) we can clearly see that addition of nanoparticles helps to reduce the crater wear on rake surface. The reason behind this is also rolling effect (ball bearing effect) of nanoparticles causes for reduction in area of contact which makes the flow of chip over rake surface easy, whereas in case of normal MQL environment tool chipping effect can be easily judge on tool edge under roughening mode condition by looking at image itself (Fig.

22(b)), it is due to absence of Al_2O_3 nanoparticles. For 8 vol% concentration effect of restricted flow of Al_2O_3 nanoparticles results in adhesion of workpiece material due to increase in surface roughness which is visible under finishing mode running condition, however inclusion of nanoparticles able to provide rolling effect as per is tendency whose result can be easily compare in term of less tool-chip contact length.

5.6 Effect on chip reduction coefficient (*ζ*)

Chip reduction coefficient can be defined as the ratio of chip thickness to uncut chip thickness. As the values of chip thickness always comes greater than that of uncut chip thickness, chip reduction coefficient always lies above 1. This phenomenon concern with shearing failure of the chip due to which chip gets deformed and its thickness gets increased.

$$\zeta = \frac{Chip\ thickness}{Uncut\ chip\ thickness}$$



(a) (b)

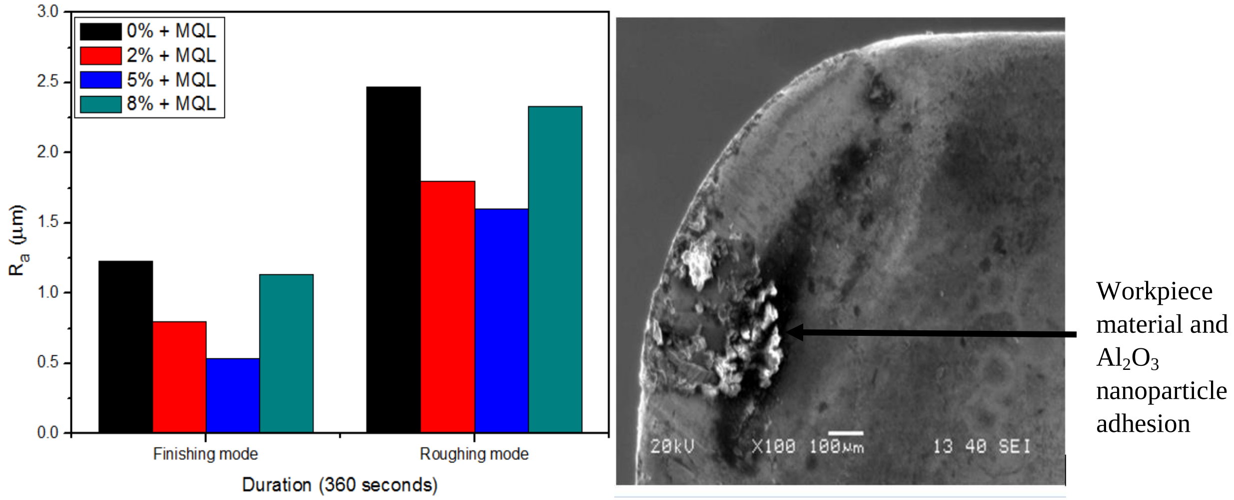
Fig. 24: Chip reduction coefficient values along with chip images after 360th seconds of run for (a) finishing mode (b) roughing mode running conditions

Graphs 24 (a) and 24 (b) are on aim to find out chip thickness behavior in order to understand the deformation amount of chip. From the graphs it can say that inclusion of Al_2O_3

nanoparticles plays an important role in order to reduce the value of chip thickness thereby reduces the value of chip reduction coefficient. As due to presence of nanoparticles chip easily flows over the tool face due to which chances of long accumulation of deformed chip over tool reduces, which results in reduced values of chip thickness.

5.7 Effect on surface roughness (R_a)

The quality of any machined surface is defined by of surface roughness. It is a component surface texture component. Surface roughness is a one of determining factor to identify that how areal object will interact with its surrounding. It has been seen that irregularities in the surface may promote cracks or corrosion. Adhesion phenomenon can be seen in presence of higher values surface roughness.



(a) (b)

Fig. 25: (a) variation in surface roughness corresponding to inclusion of Al_2O_3 nanoparticles, (b) rake surface of tool under 8 vol% concentration of Al_2O_3 nanoparticles under finishing mode condition

From the fig. 25 (a) the beneficial aspects of nanoparticles inclusion can be draw in term of reducing surface roughness. This occurrence is following polishing effect (fig. 26) of nanoparticles [32]. Polishing effect comes due to irregularity in size of sharp edges Al_2O_3 nanoparticles helps to remove formed burrs. Rubbing action of nanoparticles helps to reduce the unevenness nature of machined surface. However, under roughing mode in case of 8 vol% inclusion the adverse effect of restricted flow nanoparticles is evidence of getting higher values of surface roughness following by adhesion of workpiece and non-conducting Al_2O_3 nanoparticles in the rake surface 25 (b).

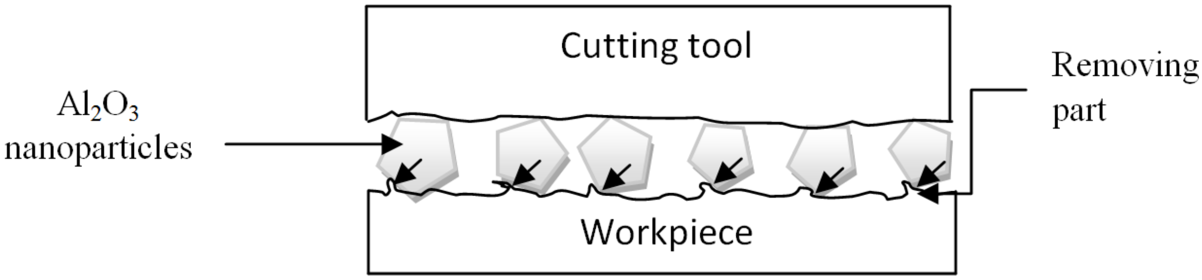


Fig. 26: Polishing effect of nanoparticles on workpiece

5.8 Effect on chip morphology

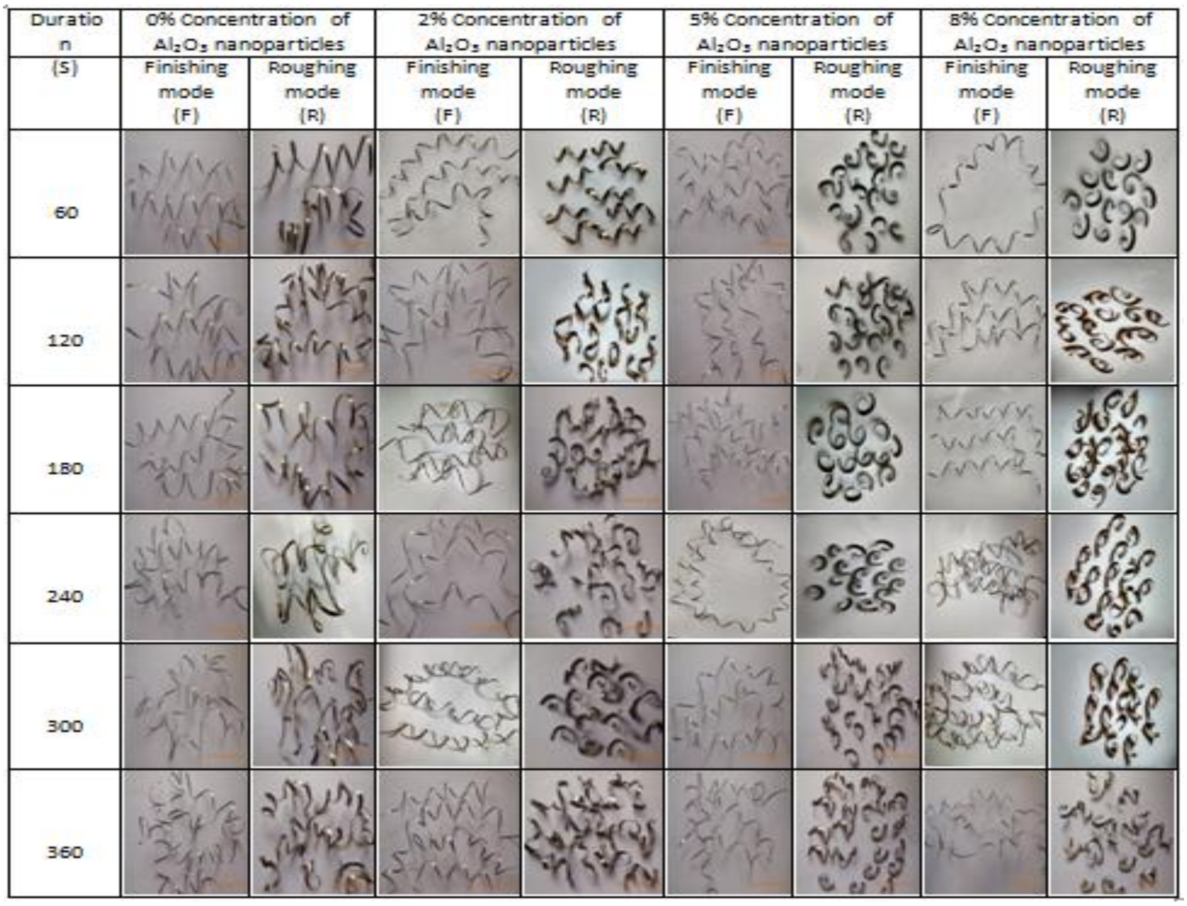
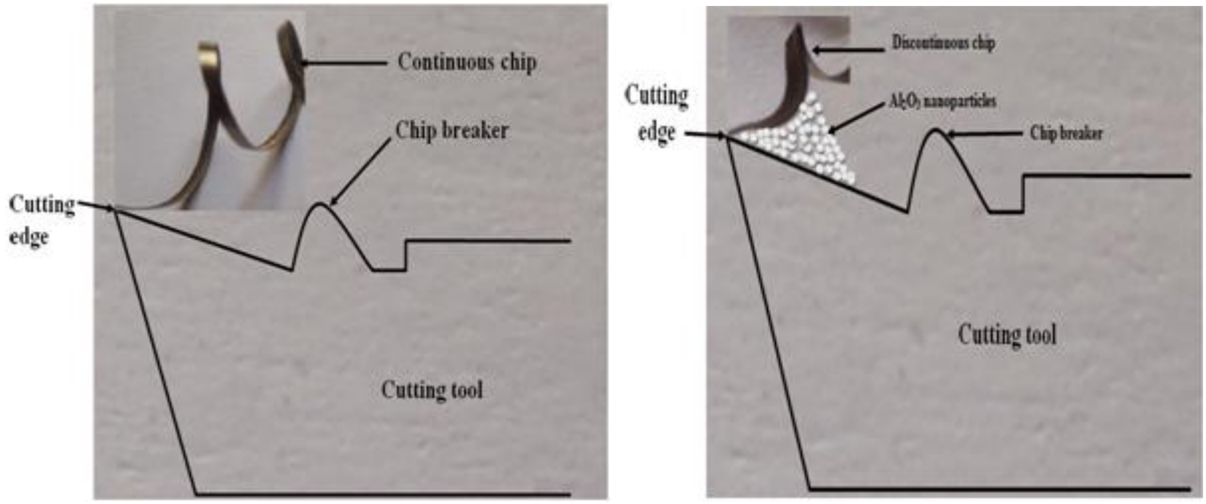


Fig. 27: Conditions of formed chip under different condition of MQL environment

Fig. 27 is the evidence of chip breaking effect of nanoparticles under roughing mode running conditions. as it has been clearly seen that for finishing mode conditions formed chip followed almost same trend, whereas in case of roughening mode running conditions for normal MQL condition (without additives) continuous chips formation takes place whereas in case of nanoparticle included MQL environment segmented and discontinuous types of chip produced.



(a) (b)

Fig. 28: (a) Chip formation phenomenon under normal MQL environment and (b) MQL with nanoparticles additives

From the fig 28 (b) and 28 (b) shows the mechanism behind segmented and discontinuous chip formation under roughing mode machining conditions. Figure clearly explained that on absence of nanoparticles curling nature of chip restricted the chances of flow of chip over chip breaker thereby continuous chip forming phenomenon take place, whereas in case of nanoparticles inclusion conditions millions of Al_2O_3 nanoparticles acts as unified chip breaker at the nearest to cutting zone and because high fluid pressure chip experienced backward force which causes for breaking of chip thereby by segmented and discontinuous chips forms.

CHAPTER 6

CONCLUSION

The present research work aimed at investigating the use of Al_2O_3 nanoparticles mixed with base cutting fluid under MQL environment. Both finishing and roughing mode of machining were considered to determine the suitability of usage of nanofluid lubrication. Following conclusion can be inferred from the current study:

- Addition of Al_2O_3 nanoparticles to the base cutting fluid results in remarkable reduction in cutting forces, dynamic fluctuation of cutting forces, cutting temperature, tool wear, and surface roughness as compare to conventional MQL (without additives).
- 5 vol% exhibits best performance while further increasing of Al_2O_3 nanoparticles concentration worsened the performance.
- Chips obtained under conventional MQL was mostly continuous in nature while those obtain under nanofluid lubricating environment were of broken type.
- Since nanofluid lubrication has clearly demonstrated significant decrease in consumption of cutting fluid as well as the cutting energy or cutting power while improving surface quality, this technique has been established as a environmentally friendly green manufacturing or sustainable manufacturing.

Future scope of work

- Effect of nozzle orientation and different base fluid can also be studied on different machining characteristics during nanofluid lubrication.
- In depth cost analysis can be performed and correlated with the performance during dry, conventional flood cooling, MQL and nanofluid lubrication.
- Effect of nanofluid lubrication can be studied in detained on machined surface integrally.

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